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Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030

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Executive Summary

Greenhouse gases other than carbon dioxide (CO_2) play an important role in the effort to understand and address global climate change. Non-carbon dioxide (non-CO_2) greenhouse gases include methane (CH_4), nitrous oxide (N_2O), and a number of high global warming potential or fluorinated gases. The non-CO_2 greenhouse gases are more potent than CO_2 (per unit weight) at trapping heat within the atmosphere and, once emitted, can remain in the atmosphere for either shorter or longer periods of time than CO_2. Approximately 30% of the anthropogenic greenhouse effect since preindustrial times can be attributed to these non-CO_2 greenhouse gases (Intergovernmental Panel for Climate Change [IPCC], 2001b); approximately 25% of GWP-weighted greenhouse gas emissions in the year 2005 comprise the non-CO_2 greenhouse gases (U.S. Environmental Protection Agency [USEPA], 2012).

Greenhouse gases are the primary driver of climate change, which can lead to hotter, longer heat waves that threaten the health of the sick, poor, or elderly; increases in ground-level ozone pollution linked to asthma and other respiratory illnesses; and other threats to human health and welfare. In some cases, reducing non-CO_2 emissions can have a more rapid effect on the climate and be more cost-effective than reducing CO_2 emissions. Given the important role that mitigation of non-CO_2 greenhouse gases can play in climate strategies, there is a clear need for an improved understanding of the mitigation potential for non-CO_2 sources, as well as for the incorporation of non-CO_2 greenhouse gas mitigation in climate economic analyses. This report is a follow-on to the 2006 EPA report *Global Mitigation of Non-CO₂ Greenhouse* Gases and illustrates the abatement potential of non-CO_2 greenhouse gases through a comprehensive global analysis and resulting data set of marginal abatement cost (MAC) curves.

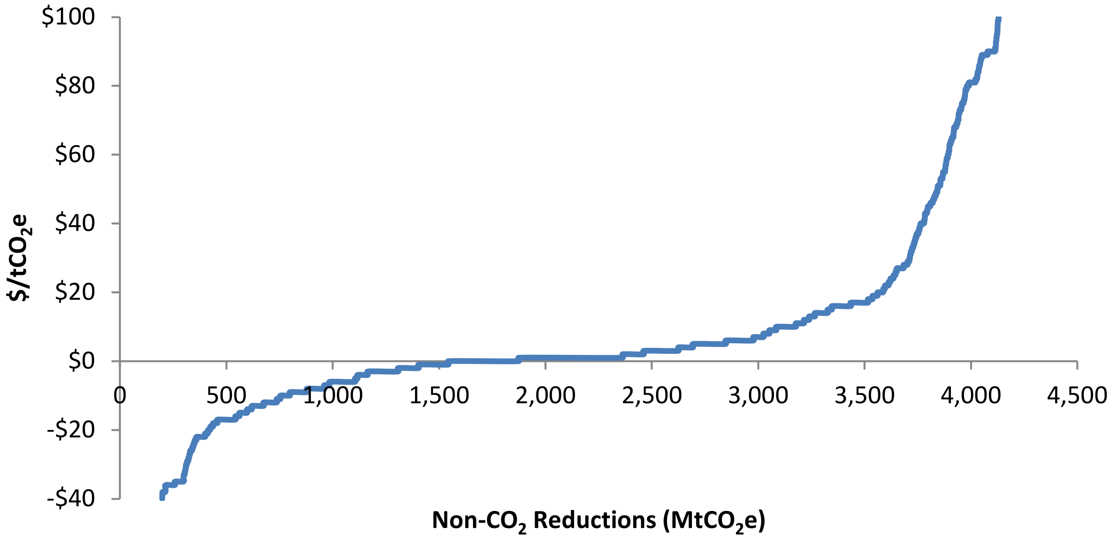
The report provides a comprehensive global analysis and resulting data set of MACs that illustrate the abatement potential of non-CO_2 greenhouse gases by sector and by region. This analysis incorporates updated mitigation technologies, costs, and emissions baselines with an updated modeling approach. The results of the analysis are MAC curves that reflect aggregated break-even prices for implementing mitigation options in a given sector and region with more detail than available in the previous report. This assessment of mitigation potential is unique because it is comprehensive across all non-CO_2 greenhouse gases, across all emitting sectors of the economy, and across all regions of the world. The MAC curves allow for improved understanding of the mitigation potential for non-CO_2 sources, as well as inclusion of non-CO_2 greenhouse gas mitigation in economic modeling of multigas mitigation strategies.

The basic methodology—a bottom-up, engineering cost approach—is the same as the methodology followed in the 2006 report. Building on the baseline non-CO_2 emissions projections from the USEPA's *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2030* (2012), this analysis applies mitigation options to the emissions baseline in each sector. The technical abatement potential and cost are calculated for each mitigation option across all the emitting greenhouse gas sectors. The average break-even price is calculated for the estimated abatement potential for each mitigation option. The options are then ordered in ascending order of break-even price (cost) and plotted against abatement potential. The resulting MAC is a stepwise function; each point on the curve represents the break-even price point for a discrete mitigation option (or defined bundle of mitigation strategies) and the associated abatement potential. This report makes no explicit assumption about policies that would be required to facilitate and generate adoption of mitigation options. Therefore, this report provides estimates of technical mitigation potential.

The results of this analysis are MAC curves that reflect the prices for implementing mitigation options in a given sector and region. This report provides improved data to better understand the mitigation potential for non-CO_2 sources and allows for inclusion of non-CO_2 greenhouse gas mitigation approaches in economic modeling of multigas mitigation strategies. The MAC data sets can be downloaded in spreadsheet format from the USEPA Web site at http://www.epa.gov/climatechange/EPAactivities/economics/nonco2mitigation.html.

Mitigation of Non-CO_2 Gases Can Play an Important Role in Climate Strategies. Worldwide, the potential for cost-effective non-CO_2 greenhouse gas abatement is significant. Figure ES-1 shows the global total aggregate MAC for the year 2030. Without a price signal (i.e., at \$0/tCO_2e), the global mitigation potential is greater than 1,800 million metric tons of CO_2 equivalent ($MtCO_2e$), or 12% of the baseline emissions (refer to Section I.3.3 of this report for a more detailed explanation of unrealized mitigation potential in the MACs). As the break-even price rises, the mitigation potential grows. Significant mitigation opportunities could be realized in the lower range of break-even prices. The global mitigation potential at a price of \$10/tCO_2e is greater than 3,000 $MtCO_2e$, or 20% of the baseline emissions, and greater than 2,400 $MtCO_2e$ or 24% of the baseline emissions at \$20/tCO_2e. In the higher range of break-even prices, the MAC becomes steeper, and less mitigation potential exists for each additional increase in price.

Figure ES-1: Global Total Aggregate MAC for Non-CO_2 Greenhouse Gases in 2030



Globally, the Sectors with the Greatest Potential for Mitigation of Non-CO_2 Greenhouse Gases are the Energy and Agriculture Sectors. Figure ES-2 shows the global MACs by economic sector in 2030. At a break-even price of \$5/tCO_2e, the potential to reduce of non-CO_2 greenhouse gases is greater than 1,190 $MtCO_2e$ in the energy sector and approximately 1,080 $MtCO_2e$ in the industrial process sector. At a break-even price of \$30/tCO_2e, the potential increases to approximately 1,475 $MtCO_2e$ in the industrial sector, nearly 1,400 $MtCO_2e$ in the energy sector, and 500 and 332 $MtCO_2e$ in the agriculture and waste sectors, respectively.

Methane Mitigation has the Largest Potential across All the Non-CO_2 Greenhouse Gases. Figure ES-3 shows the global MACs by greenhouse gas type for 2030. At or below \$0/tCO_2e, the potential for CH_4 mitigation is greater than 1,000 MtCO_2e. The potential for reducing CH_4 emissions grows to over 2,000 MtCO_2e as the break-even price rises from \$0 to \$30/tCO_2e, while less than that of CH_4, N_2O, and F-gases exhibit significant mitigation potential at or below \$0/tCO_2e.

Figure ES-2: Global 2030 MACs for Non-CO_2 Greenhouse Gases by Major Sector

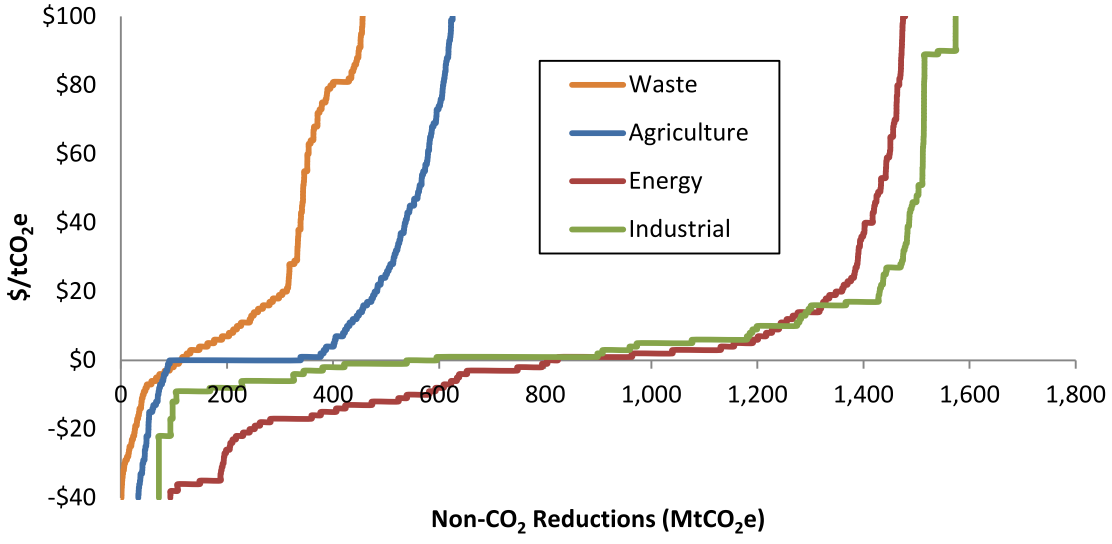
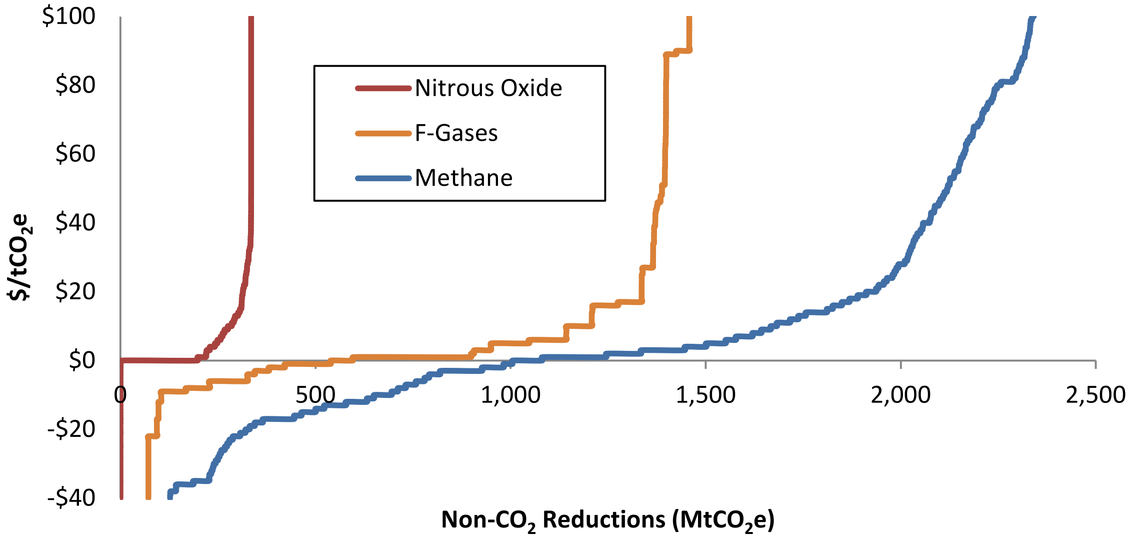
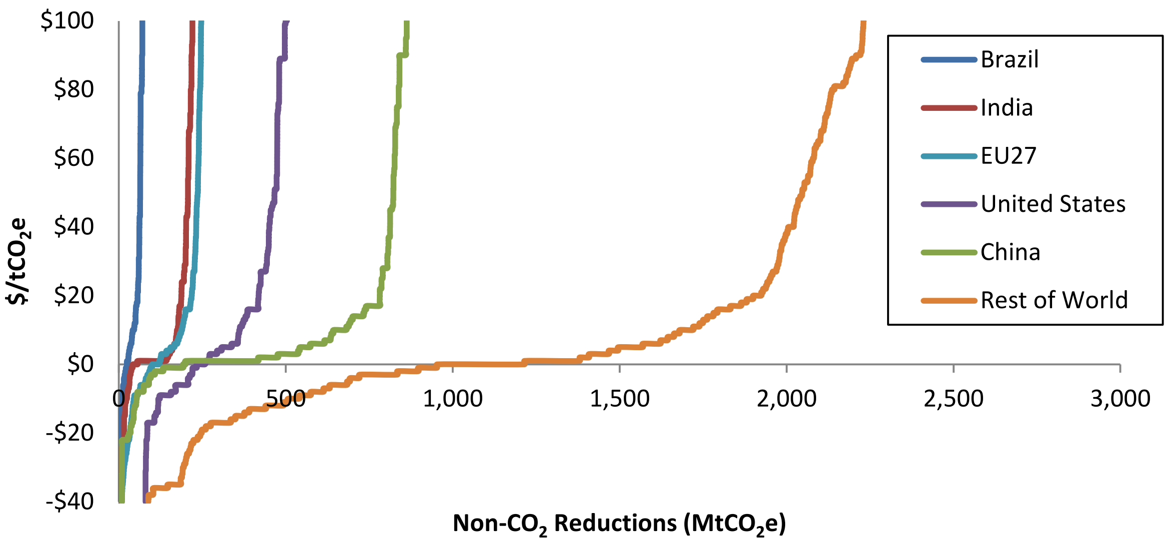


Figure ES-3: Global 2030 MACs by Non-CO_2 Greenhouse Gas Type



Major Emitting Regions of the World Offer Large Potential Mitigation Opportunities. Figure ES-4 shows the global MACs by region for 2030. The United States and China are the top two contributors to global mitigation potential with cost-effective mitigation of 260 and 200 $MtCO_2e$, respectively. The largest sources of mitigation potential in these regions are oil/gas, refrigeration/ac, livestock, and coal. The EU, India, and Brazil represent significant mitigation potential as well. At a break-even price of $30/$tCO_2e$ the five largest emitting countries represent 46% of the global abatement potential.

Figure ES-4: Global 2030 MACs for Non-CO_2 Greenhouse Gases by Major Emitting Regions



The aggregate MACs by economic sector, greenhouse gas type, and region highlight the importance of including non-CO_2 greenhouse gases in the analysis of multigas climate strategies. The MACs illustrate that a significant portion of this emissions reduction potential can be realized at zero or low carbon prices. The mitigation potential in each economic sector is examined in greater detail in this report.

References

Intergovernmental Panel on Climate Change (IPCC). 2001b. *Technical Summary: A Report Accepted by Working Group I of the IPCC but not approved in detail*. A product resulting from The Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change, January 2001. Available at: www.ipcc.ch.

U.S. Environmental Protection Agency (USEPA). (2012a). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Available at: http://www.epa.gov/climatechange/economics/international.html.

I. Technical Summary

I.1 Overview

The objective of this peer reviewed technical report is to provide a comprehensive and consistent data set on global mitigation of noncarbon dioxide (non-CO_2) greenhouse gases by sector and by region. Mitigating emissions of non-CO_2 greenhouse gases can be relatively inexpensive compared with mitigating CO_2 emissions. Thus, attention continues to focus on incorporating international non-CO_2 greenhouse gas mitigation options into climate economic analyses. This requires a large data collection effort and expert analysis of available technologies and opportunities for greenhouse gas reductions across diverse regions and sectors.

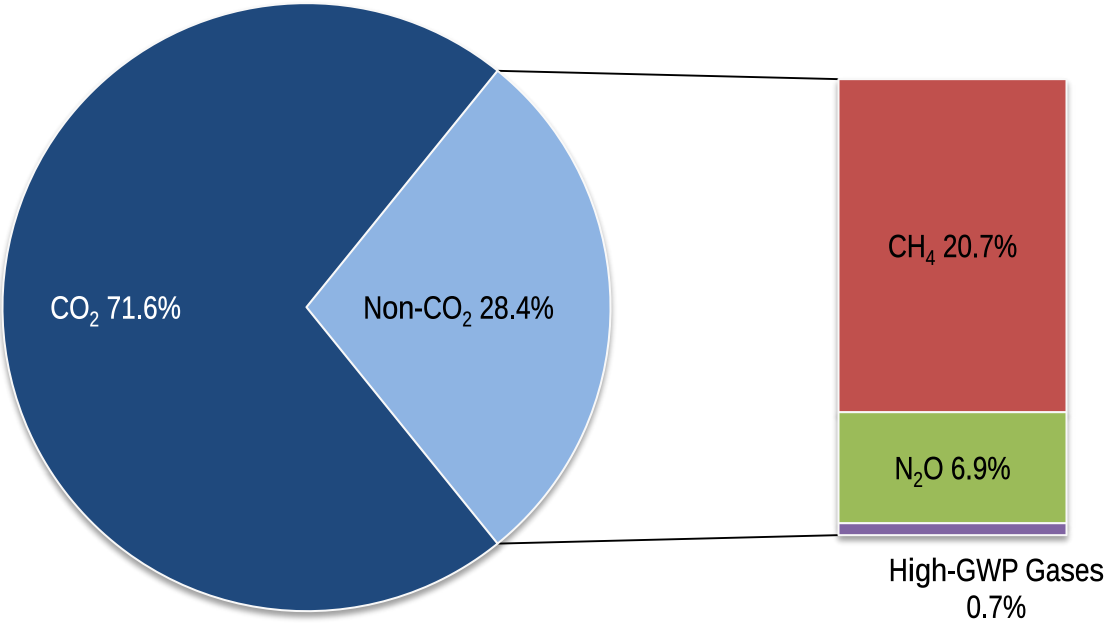
This report is an update to the 2006 EPA report, *Global Mitigation of Non-*CO_2 *Greenhouse Gases*, and incorporates an updated modeling approach and new data on mitigation technologies, costs, and emissions baselines. The basic methodology—a bottom-up, engineering cost approach—is the same as was followed in the 2006 report, with some enhancements (as described in Section I.3.4 of this report). The results of this analysis are marginal abatement cost (MAC) curves. The end result of this report is a set of marginal abatement curves (MACs) that allow for improved understanding of the mitigation potential for non-CO_2 sources, as well as inclusion of non-CO_2 greenhouse gas mitigation in economic modeling. The MAC data sets can be downloaded in spreadsheet format from the USEPA's Web site at http://www.epa.gov/climatechange/EPAactivities/economics/nonco2mitigation.html.

I.2 Non-CO_2 Greenhouse Gases

Greenhouse gases other than CO_2 play an important role in the effort to understand and address global climate change. The non-CO_2 gases include methane (CH_4), nitrous oxide (N_2O), and a number of high global warming potential or fluorinated gases. The non-CO_2 greenhouse gases are more potent than CO_2 (per unit weight) at trapping heat within the atmosphere and, once emitted, can remain in the atmosphere for either shorter or longer periods of time than CO_2. Figure I-1 shows that these non-CO_2 greenhouse gases are responsible for approximately 30 percent of the enhanced, anthropogenic greenhouse effect since preindustrial times.

Table I-1 shows the global total greenhouse gas emissions for the year 2010, broken down by sector and by greenhouse gas type. The non-CO_2 gases constitute 28 percent of the global total greenhouse gas emissions.

Figure I-1: Contribution of Anthropogenic Emissions of Greenhouse Gases to the Enhanced Greenhouse Effect from Preindustrial to Present (measured in watts/meter^2)



Source: Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table I-1: Global Non-CO_2 Greenhouse Gas (GHG) Emissions for 2010 ($MtCO_2e$) by Source and Gas Type

Sectors	CH_4	N_2O	F-Gases	Global Total Non-CO_2 Emissions	Percentage of Global Total Non-CO_2 GHGs
Agriculture	3,102	2,897	—	5,999	53%
Energy	2,991	54	—	3,044	27%
Industry	83	118	672	873	8%
Waste	1,374	97	—	1,471	13%
Global Total	7,549	3,166	672	11,387	
Percentage of Global Total Non-CO_2 GHGs	66%	28%	6%		

Source: USEPA. 2012. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 -2030.* EPA 430-S-12-006. USEPA: Washington D.C. Available at: http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html

I.2.1 Methane (CH_4)

CH_4 is about 21 times more powerful at warming the atmosphere than CO_2 over a 100-year period (IPCC, 1996). In addition, CH_4's chemical lifetime in the atmosphere is approximately 12 years, compared with approximately 100 years for CO_2. These two factors make CH_4 a candidate for mitigating global warming in the near term (i.e., within the next 25 years or so) or in the time frame during which atmospheric concentrations of CH_4 could respond to mitigation actions.

CH_4 is emitted from a variety of manmade sources, including landfills, oil and natural gas systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes. CH_4 is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent or capture and use CH_4 emissions can provide significant energy, economic, and environmental benefits.

I.2.2 Nitrous Oxide (N_2O)

N_2O is a clear, colorless gas with a slightly sweet odor. Because of its long atmospheric lifetime (approximately 120 years) and heat-trapping effects—about 310 times more powerful than CO_2 on a per-molecule basis—N_2O is an important greenhouse gas.

N_2O has both natural and manmade sources and is removed from the atmosphere mainly by photolysis (i.e., breakdown by sunlight) in the stratosphere. In the United States, the main manmade sources of N_2O are agricultural soil management, livestock waste management, mobile and stationary fossil fuel combustion, adipic acid production, and nitric acid production. N_2O is also produced naturally from a variety of biological sources in soil and water.

I.2.3 F-Gases Gases

There are three major groups or types of F-Gases gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). These compounds are the most potent greenhouse gases because of their large heat-trapping capacity and, in the cases of SF_6 and the PFCs, their extremely long atmospheric lifetimes. Because some of these gases, once emitted, can remain in the atmosphere for centuries, their accumulation is essentially irreversible. F-Gases gases are emitted from a broad range of industrial sources; most of these gases have few (if any) natural sources.

HFCs

HFCs are manmade chemicals, many of which have been developed as alternatives to ozone-depleting substances (ODSs) for industrial, commercial, and consumer products. The GWPs of HFCs range from 140 (HFC-152a) to 11,700 (HFC-23). The atmospheric lifetime for HFCs varies from just over a year (HFC-152a) to 260 years (HFC-23). Most of the commercially used HFCs have atmospheric lifetimes of less than 15 years (for example, HFC-134a, which is used in automobile air-conditioning and refrigeration, has an atmospheric lifetime of 14 years).

PFCs

Primary aluminum production, semiconductor manufacturing and flat panel display manufacturing are the largest known manmade sources of tetrafluoromethane (CF_4), and hexafluoroethane (C_2F_6). PFCs are also relatively minor substitutes for ODSs. Over a 100-year period, CF_4 and C_2F_6 are, respectively, 6,500 and 9,200 times more effective than CO_2 at trapping heat in the atmosphere.

Sulfur Hexaflouride (SF_6)

The GWP of SF_6 is 23,900, making it the most potent greenhouse gas evaluated by IPCC. SF_6 is a colorless, odorless, nontoxic, nonflammable gas with excellent dielectric properties. It is used (1) for insulation and current interruption in electric power transmission and distribution equipment; (2) to protect molten magnesium from oxidation and potentially violent burning in the magnesium industry; (3) to create circuitry patterns and to clean vapor deposition chambers during manufacture of semiconductors and flat panel displays; and (4) for a variety of smaller uses, including uses as a tracer gas and as a filler for sound-insulated windows.

Like the PFCs, SF_6 is very long lived, so all manmade sources contribute directly to its accumulation in the atmosphere. Measurements of SF_6 show that its global average concentration increased by about 7 percent per year during the 1980s and 1990s, from less than 1 ppt in 1980 to almost 4 ppt in the late 1990s (IPCC, 2001a).

I.2.4 Use of GWPs in this Report

The GWP compares the relative ability of each greenhouse gas to trap heat in the atmosphere during a certain time frame. Per IPCC (1996) guidelines, CO_2 is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH_4 is 21 and the GWP of N_2O is 310. Table I-2 lists all GWPs used in this report to convert the non-CO_2 emissions into CO_2-equivalent units. This report uses GWPs from the 1996 IPCC Second Assessment Report (rather than the 2001 Third Assessment Report) because these are the values specified by greenhouse gas reporting guidelines under the United Nations Framework Convention on Climate Change.

Table I-2: Global Warming Potentials

Gas	GWP[a]
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

Source: IPCC, 1996.
[a] 100 year time horizon.

I.3 Methodology

This section describes the basic methodology used in this report to analyze potential emissions and abatement of non-CO_2 greenhouse gases. The analysis builds on the approach presented in the 2006 Global Mitigation of Non-CO_2 Greenhouse Gases report (USEPA, 2006a). For the current analysis several enhancements were made for the MAC analysis and these will be highlighted in the discussion that follows. Primary enhancements include:

- Updating baseline emissions projections
- Disaggregating mitigation potential and costs to the country level for 195 countries
- Updating reduction efficiencies for individual measures by country
- Updating capital and operation and maintenance (O&M) costs for individual measures
- Segmenting O&M costs into labor, materials and energy components
- Developing international adjustments factors used to construct country specific abatement costs and benefits
- Updating crop process model simulations of changes in crop yields and emissions associated with rice cultivation and cropland soil management

MAC curves are constructed for each region and sector by estimating the carbon price at which the present value benefits and costs for each mitigation option equilibrates. The methodology produces a stepwise curve, where each point reflects the average price and reduction potential if a mitigation technology were applied across the sector within a given region. In conjunction with appropriate baseline and projected emissions for a given sector the results are expressed in terms of absolute reductions of carbon dioxide equivalents ($MtCO_2e$).This section describes the components of our methodology.

First, we establish the baseline emissions for each sector as described in Section I.3.1. Section I.3.2 presents the methodology used to evaluate mitigation options, which involves calculating the abatement potential and the breakeven price for each option. Lastly, we describe the construction of the MACs in Section I.3.3. Some sectors deviate from this methodology depending on specific circumstances, which are briefly mentioned here and described in more detail in the sector-specific chapters.

The results of the analysis are presented as MACs by region and by sector and generally focus on the 2010 to 2030 time frame. Emissions abatement in the MACs is shown as both absolute emissions reductions and as percentage reductions from the baseline. Non-CO_2 emissions sources analyzed in this report are

- coal mining;
- oil and natural gas systems;
- solid waste management;
- wastewater;
- specialized industrial processes; and
- agriculture.

I.3.1 Baseline Emissions for Non-CO_2 Greenhouse Gases

For consistency across regions and sectors the MAC Report analysis primarily uses the EPA report, *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030* for baseline emissions and projections. The Global Emissions Report (GER) was published in December of 2012, and uses a combination of country-prepared, publicly-available reports (UNFCCC National Communications) and IPCC Tier 1 methodologies to fill in missing or unavailable data. The basis for the U.S. historical emissions in the GER is the U.S. Inventory of Greenhouse Gases and Sinks published in April of 2011. The methods used to estimate and project non-CO_2 emissions in USEPA (2012) are briefly summarized here. In some cases, particularly for agricultural emissions, it was necessary to develop separate baselines from which to assess the mitigation analyses. For the agricultural sector, the baseline emissions used in this report were based on crop process model simulations and livestock population data combined with projected crop areas and livestock populations, respectively, from the International Food Policy Research Institute

International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. These deviations are also explained in more detail in this report.

The preferred approach for estimating historical and projected emissions is to use country-prepared, publicly-available reports. EPA applied an overarching methodology to estimate emissions across all sectors, and deviations to this methodology are discussed in each of the source-specific methodology sections of USEPA (2012). The following summary of the general methodology used to estimate global non-CO_2 emissions is replicated from the USEPA (2012) report.

Historical Emissions

For Annex I Countries (A1), the UNFCCC flexible query system (UNFCCC, 2012) provides emission estimates for A1 countries from Common Reporting Format (CRF) files, submitted with annual national inventories. The full or partial time series of source disaggregated data is available for A1 countries from 1990 through 2007. The time series is complete for the majority of sources; however there are gaps in the time series for some countries and categories and data for missing years were supplemented. The methodology used by each source to interpolate, backcast, or forecast depends on the availability of CRF data and the distribution of that data over time. In general, the following methodology was applied to interpolate, backcast, or forecast data:

- When two years are reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), EPA interpolates the missing estimate (1995) using reported estimates.
- EPA backcasted or forecasted emission estimates to complete the historical series for 1990, 1995, 2000, and 2005 on a source by source basis. For each source, EPA used growth rates for available activity data believed to best correlate with emissions (e.g., production, consumption). If either 1) more than one type of activity data should be used, 2) the emission factor will vary over time, or 3) the relationship between the activity data and emissions is not linear (i.e., exponential), then EPA used Tier 1 growth rates. This involves estimating emissions for 1990, 1995, 2000, and 2005 using a Tier 1 approach, then using the rate of growth of this emission estimate to backcast and forecast the country-reported emissions.
- If a country-reported an estimate for an individual source for one year, but reported aggregate estimates for other years, EPA disaggregated the estimates using the percent contribution of the individual source in the latest reported year.

For Non-Annex I countries historical emissions data were available in the UNFCCC flexible query system as well, but generally these reported data do not constitute a full time series. The methodology for interpolating or backcasting missing historical data used by each source will follow the same general guidelines outlined in the earlier in this section. Because the data for non-A1 countries from the UNFCCC flexible query system do not generally have a complete time series, it is likely that non-A1 sources will rely more heavily on Tier 1 calculated growth rates or activity data growth rates for backcasting and forecasting emissions between 1990 and 2005.

Projected Emissions

Emission projections by source and country were obtained from National Communications (NCs) reports. For A1 countries, this refers to the Fifth NCs currently being released. For non-A1 countries, EPA reviewed the most recent NCs submitted to the UNFCCC.

If an NC had projections for a sector but not a source, EPA used the relative proportion of emissions for the latest year of historical emissions to disaggregate projected emissions for a source. For example, if France projected CH_4 emissions from agriculture to 2030 but does specify what portion is from manure management, EPA took the proportion of emissions that manure contributes to agriculture CH_4 emissions in France's 2007 GHG Inventory, assume this proportion remains constant for 2030, and apply this to the 2030 agriculture estimate.

If projections for a sector are not available from a NC, EPA used activity data drivers or Tier 1 growth rates, specific to each source. The specific methodology followed by each source category is outlined in each sector's methodology description.

For most countries, emissions and projections are not available for the sources of F-GHGs. Therefore, EPA estimates F-GHG emissions and projections using detailed source methodologies described in USEPA (2012).

Baseline Emissions for Agriculture

Although USEPA (2012) contains estimates of baseline emissions for agricultural sources, alternative baselines were developed for the purposes of the mitigation report. The primary rationale was to ensure consistency in the area, number of livestock head, production, and price projections used across the entire agricultural sector. Projections provided by IFPRI from their IMPACT model of global agricultural markets were used to adjust values for agricultural activities and associated emissions over time. In addition, detailed process-based models—Daily Century (DAYCENT) for croplands and DeNitrification–DeComposition (DNDC) for rice cultivation—were used for both the baseline emissions estimates and the greenhouse gas implications of mitigation options, thus allowing for a clear identification of baseline management conditions and consistent estimates of changes to those conditions through mitigation activities. Emissions obtained using these detailed simulation models differ from those obtained in USEPA (2012), which relied upon IPCC default emissions factors. For emissions associated with livestock, the mitigation analysis in this report relies on projections similar to those used in USEPA (2012), but with some differences due to the adjustments made for consistency with IFPRI IMPACT projections across all agricultural sectors. The baseline emissions were also disaggregated by livestock production system and intensity using data provided by the United Nations Food and Agriculture Organization (FAO). Further details about the emissions baselines estimated by the DAYCENT and DNDC models, and their relationship to USEPA (2012) estimates, are provided in Section V Agriculture of this report.

I.3.2 Mitigation Option Analysis Methodology

Mitigation options represented in the MACs of this report are applied to the baselines described in Section IV.1.3.1. The mitigation option analysis throughout this report was conducted using a common methodology and framework. This section outlines the basic methodology. The sector-specific chapters describe the mitigation estimation methods in greater detail, including any necessary deviations from the basic methodology.

The abatement analysis for all non-CO_2 gases for agriculture, coal mines, natural gas systems, oil systems, landfills, wastewater treatment, and nitric and adipic acid production are based on USEPA , 2006 and improve upon DeAngelo et al. (2006), Beach et al. (2008), Delhotal et al. (2006), and Ottinger et al. (2006). These studies provided estimates of potential CH_4 and N_2O emissions reductions from major emitting sectors and quantified costs and benefits of these reductions.

Given the detailed data available for U.S. sectors, the USEPA's U.S. analysis uses representative facility estimates but then applies the estimates to a highly disaggregated and detailed set of emissions sources for all the major sectors and subsectors. For example, the USEPA analysis of the natural gas sector is based on more than 100 emissions sources in that industry, including gas well equipment, pipeline compressors and equipment, and system upsets. Thus, the USEPA analysis provides significant detail at the sector and subsector levels.

The analysis generally begins with developing sector level model facilities or units to which mitigation options are applied. In many cases the model facilities, abatement costs and mitigation potential are based on detailed US and EU inventory estimates, and then extrapolate to "model" facilities for other countries. For some sectors, such as wastewater, landfills, and selected industrial sectors, additional detail on international abatement options and costs are available and are incorporated into the model.

A scaling factor is used to reconcile inventory data with the GER baseline emissions data. For the F-Gases abatement analysis, natural gas and oil, and landfills sectors it is assumed that some mitigation technologies are adopted to meet future regulations or voluntary industry reduction targets. Therefore, some mitigation options are accounted for in the baseline emissions. If an option is assumed to be adopted in the baseline, it is not included when generating the MAC. In addition, expert judgment determines market shares for mitigation technologies competing for the same set of emissions (when multiple options are available that are substitutes for each other).

The agricultural sector's emissions abatement analysis improves upon previous studies supported by the USEPA (USEPA, 2006; DeAngelo et al., 2006; Beach et al., 2008) that generated MACs by major world region for cropland N_2O, livestock enteric CH4, manure management CH4, and rice cultivation CH4. The most significant change in this report is the use of updated versions of the biophysical, process-based models used in previous studies (i.e., DAYCENT and DNDC) applied at a more disaggregated spatial scale to better capture the net greenhouse gas and yield effects and to capture the spatial and temporal variability of those effects for the cropland and rice emissions baseline and mitigation scenarios. Use of these process-based models is intended to show broad spatial and temporal baseline trends and broad changes when mitigation scenarios are introduced, rather than to show definitive absolute emissions numbers for specific locations. In addition, baseline emissions estimates have been updated and a larger number of mitigation options are now assessed, particularly for rice cultivation (e.g., increased emphasis on options that reduce N_2O as well as CH_4). Considerably greater disaggregation of the baseline by production system has been incorporated to improve our ability to characterize technical applicability for different types of livestock and cropping systems. More detailed results are provided for rice cultivation under deepwater, upland, rainfed, and irrigated conditions, with separate calculations for alternative irrigated water management strategies and for livestock management based on livestock production system and management intensity.

Technical Characteristics of Abatement Options

The non-CO_2 abatement options evaluated in this report are compiled from the studies mentioned above, as well as from the literature relevant for each sector. For each region, either the entire set of sector-specific options or the subset of options determined to be applicable is applied. Options are omitted from individual regions on a case-by-case basis, using either expert knowledge of the region or technical and physical factors (e.g., appropriate climate conditions). In addition, the share or extent of applicability of an option within different regions may vary based on these conditions.

The selective omission of options represents a static view of the region's socioeconomic conditions. In some instances the reduction efficiency of an option improves over time reflecting anticipated technology advances. However, the applicability of options is held constant over time. Ideally, more detailed information on country-specific conditions, technologies, and experiences will be available in the future, which will enable more rigorous analyses of abatement option availability over time in each region. In addition, the average technical lifetime of an option (in years), determined using expert knowledge of the technology or recent literature, is held constant over time and across regions.

Table I-3 summarizes how the potential emission reduction is calculated for each of the available abatement options. First the technical effectiveness of each option is calculated by multiplying the options technical applicability by its market share by its reduction efficiency. This yields the percentage of baseline emissions that can be reduced at the national or regional level by a given option. This is then applied to the Emissions stream ($MtCO_2e$) to which the option is applied to yield the emissions reductions for the mitigation option.

Table I-3: Calculation of Potential Emission Reduction for an Abatement Option

Technical Applicability (%)	X	Market Share[a] (%)	X	Reduction Efficiency (%)	=	Technical Effectiveness (%)				
						Technical Effectiveness (%)	X	Baseline Unit Emissions ($MtCO_2e$)	=	Unit Emission Reduction ($MtCO_2e$)
Percentage of total baseline emissions from a particular emissions source to which a given option can be potentially applied.		Percentage of technically applicable baseline emissions to which a given option is applied; avoids double counting among competing options		Percentage of technically achievable emissions abatement for an option after it is applied to a given emissions stream		Percentage of baseline emissions that can be reduced at the national or regional level by a given option.		Emissions stream to which the option is applied		Unit emission reductions

[a] Implied market share non competing options (i.e., only one options is applicable for an emissions streams) is assumed to add to 100 percent

Technical applicability accounts for the portion of emissions from a facility or region that a mitigation option could feasibly reduce based on its application. For example, if an option applies only to the underground portion of emissions from coal mining, then the technical applicability for the option would be the percentage of emissions from underground mining relative to total emissions from coal mining.

The implied market share of an option is a mathematical adjustment for other qualitative factors that may influence the effectiveness or adoption of a mitigation option. For certain energy, waste, and agriculture sectors, it was outside the scope of this analysis to account for adoption feasibility, such as social acceptance and alternative permutations in the sequencing of adoption. For example, if n competing (overlapping) mitigation options are available for a single emissions stream, the implied market share of each of the n overlapping options is equal to $1/n$. This avoids cumulative reductions of greater than 100 percent across options. Given the lack of region-specific data for determining the relative level of diffusion among options that could compete for the same emissions stream, we applied this conservative adjustment. An example of overlapping options is the sequencing of cropland mitigation options, where the adoption of one option (e.g., conversion to no tillage) affects the effectiveness of subsequent options (e.g., reduced fertilizer applications). While this describes the basic application of the implied adoption rate in the energy, waste, and agriculture sectors, this factor is informed by expert insight into the potential market penetration over time in the industrial processes sector. For sectors such as landfills, where market share assumptions are available, customized shares that sum to one are used instead of $1/n$.

When nonoverlapping options are applied, they affect 100 percent of baseline emissions from the relevant source. Examples of two nonoverlapping options in the natural gas system are inspection and maintenance of compressors and replacement of distribution pipes. These options are applied independently to different parts of the sector and do not compete for the same emissions stream.

The reduction efficiency of a mitigation option is the percentage reduction achieved with adoption. The reduction efficiency is applied to the relevant baseline emissions as defined by technical applicability and adoption effectiveness. Most abatement options, when adopted, reduce an emissions stream less than 100 percent. If multiple options are available for the same component, the total reduction for that component is less than 100 percent.

Once the technical effectiveness of an option is calculated as described above, this percentages multiplied by the baseline emissions for each sector and region to calculate the absolute amount of emissions reduced by employing the option. The absolute amount of baseline emissions reduced by an option in a given year is expressed in million metric tons of CO$_2$ equivalent (MtCO$_2$eq).[1]

If the options are assumed to be technically feasible in a given region, the options are assumed to be implemented immediately, Furthermore, once options are adopted, they are assumed to remain in place for the duration of the analysis, and an option's parameters are not changed over its lifetime.

Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated unit of gas (tCO$_2$eq or tons of emitted gas [e.g., tCH$_4$]). The benefits include a carbon value/price expressed as \$/tCO-$_2$e. The carbon price at which an option's benefits equal the costs is referred to as the option's breakeven price.

For each mitigation option, the carbon price (*P*) at which that option becomes economically viable is calculated using the equation below (i.e., where the present value of the benefits of the option equals the present value of the costs of implementing the option). A present value analysis of each option is used to determine breakeven abatement costs in a given region. Breakeven calculations are independent of the year the mitigation option is implemented but are contingent on the life expectancy of the option. The net present value calculation solves for breakeven price *P*, by equating the present value of the benefits with the present value of the costs of the mitigation option. More specifically,

$$\underbrace{\sum_{t=1}^{T}\left[\frac{(1-TR)(P\cdot ER+R)+TB}{(1+DR)^{t}}\right]}_{\textit{Net Present Value Benefits}} = \underbrace{CC+\sum_{t=1}^{T}\left[\frac{(1-TR)RC}{(1+DR)^{t}}\right]}_{\textit{Net Present Value Costs}}$$

where

P = the breakeven price of the option (\$/tCO$_2$e);
ER = the emissions reduction achieved by the technology (MtCO$_2$e);
R = the revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost) or change in agricultural commodity prices (\$);
T = the option lifetime (years);
DR = the selected discount rate (%);

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[1] One MtCO$_2$eq equals 1 teragram of CO$_2$ equivalent (TgCO$_2$eq); 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

CC = the one-time capital cost of the option ($);
RC = the recurring (O&M) cost of the option (portions of which may be scaled based on regional labor and materials costs) ($/year);
TR = the tax rate (%); and
TB = annual tax benefit of depreciation = $\left(\frac{CC}{T}\right) \cdot TR$.

Assuming that the emissions reduction ER, the recurring costs RC, and the revenue generated R do not change on an annual basis, then we can rearrange this equation to solve for the breakeven price P of the option for a given year:

$$P = \frac{CC}{(1-TR)\cdot ER \cdot \sum_{t=1}^{T} \frac{1}{(1+DR)^t}} + \frac{RC}{ER} - \frac{R}{ER} - \frac{CC}{ER \cdot T} \cdot \frac{TR}{(1-TR)}$$

Costs include capital or one-time costs and operation and maintenance (O&M) or recurring costs. Most of the agricultural sector options, such as changes in management practices, do not have applicable capital costs, with the exception of anaerobic digesters for manure management.

Benefits or revenues from employing an abatement option can include (1) the intrinsic value of the recovered gas (e.g., the value of CH_4 either as natural gas or as electricity/heat, the value of HFC-134a as a refrigerant), (2) nongreenhouse gas benefits of abatement options (e.g., compost or digestate for waste diversion options, increases in crop yields), and (3) the value of abating the gas given a greenhouse gas price in terms of dollars per tCO_2 eq ($/$tCO_2$eq) or dollars per metric ton of gas (e.g., $/$tCH_4$, $/tHFC-134a). In most cases, there are two price signals for the abatement of CH_4: one price based on CH_4’s value as energy (because natural gas is 95 percent CH_4) and one price based on CH4’s value as a greenhouse gas. All cost and benefit values are expressed in constant year 2010 U.S. dollars. This analysis is conducted using a 10 percent discount rate and a 40 percent tax rate. For quick reference, Table I-4 lists the basic financial assumptions used throughout this report.

Table I-4: Financial Assumptions in Breakeven Price Calculations for Abatement Options

Economic Parameter	Assumption
Discount Rate	10%
Tax Rate	40%
Constant Year Dollars	2010$

International Adjustment Factors

Costs and benefits of abatement options are adjusted to reflect regional prices. Wages and prices will vary by country. Hence recurring O&M costs are segmented into labor, energy and materials costs. Material costs components range from materials and supplies in the in the industrial and energy sectors, to fertilizer costs in the agricultural sectors – all of which are likely to vary by region. One-time capital costs are assumed to relatively stable across regions and not adjusted from country to country.

For some options data were available on the relative cost shares between labor, energy and materials. For instance, in coal mining, different technologies have different cost shares which were developed based on expert judgment. For options without detailed cost breakouts, the shares are generally assigned evenly as 33% each to labor, energy, and materials. For the agricultural sector, labor, energy, water and other input costs are calculated from their shares of agricultural production costs based on social accounting matrix (SAM) data from the Global Trade Analysis Project (GTAP) v8 database and agricultural wage data from the International Food Policy Research Institute (IFPRI).

In regions where there is a lack of detailed revenue (benefits) data, revenues are scaled based on the ratio between average prices of natural gas (when CH_4 is abated and sold as natural gas) or of electricity (when CH_4 is used to generate electricity or heat) in a given region and in the United States. Similarly, revenues from non-CH_4 benefits of abatement options are scaled based on the ratio between the GDPs per capita in a given region and in the United States. In the agricultural sector, changes in revenue occur as a change in either crop yield or livestock productivity. Data on changes in crop yield or livestock productivity are combined with data on regional producer prices for the relevant agricultural commodity to calculate revenue changes.

Table I-5 lists the international economic adjustment factors for selected countries. Using publically available data on country-specific wage rates and energy prices, along with input from previous MAC analysis, indices reflecting each country's wage rates and prices relative to the United States were created. Adjustment Factors were created for labor, natural gas, electricity, coal and material costs. When data was not available for a country, the country was either mapped to a similar country (with data) or previously developed EMF factors were used.

Table I-5: International Economic Adjustment Factors for Selected Countries

Country	Labor[a]	Natural Gas[b]	Electricity[b]	Coal[b]	Materials[c]
Afghanistan	0.02	0.75	1.30	0.89	0.01
Brazil	0.24	1.30	1.60	0.76	0.13
Congo	0.19	1.06	0.34	0.37	0.05
China	0.04	0.62	0.63	0.68	0.07
India	0.03	0.67	1.69	0.69	0.02
Madagascar	0.19	1.06	0.34	0.37	0.01
Mexico	0.12	1.04	1.42	0.94	0.20
Norway	1.80	1.62	0.77	2.57	1.61
Poland	0.26	0.98	1.19	1.25	0.24
Russian Federation	0.12	0.19	0.56	0.67	0.15
Switzerland	1.35	1.62	1.41	2.04	1.30
United States	1.00	1.00	1.00	1.00	1.00
Uzbekistan	0.12	0.19	0.38	0.19	0.02

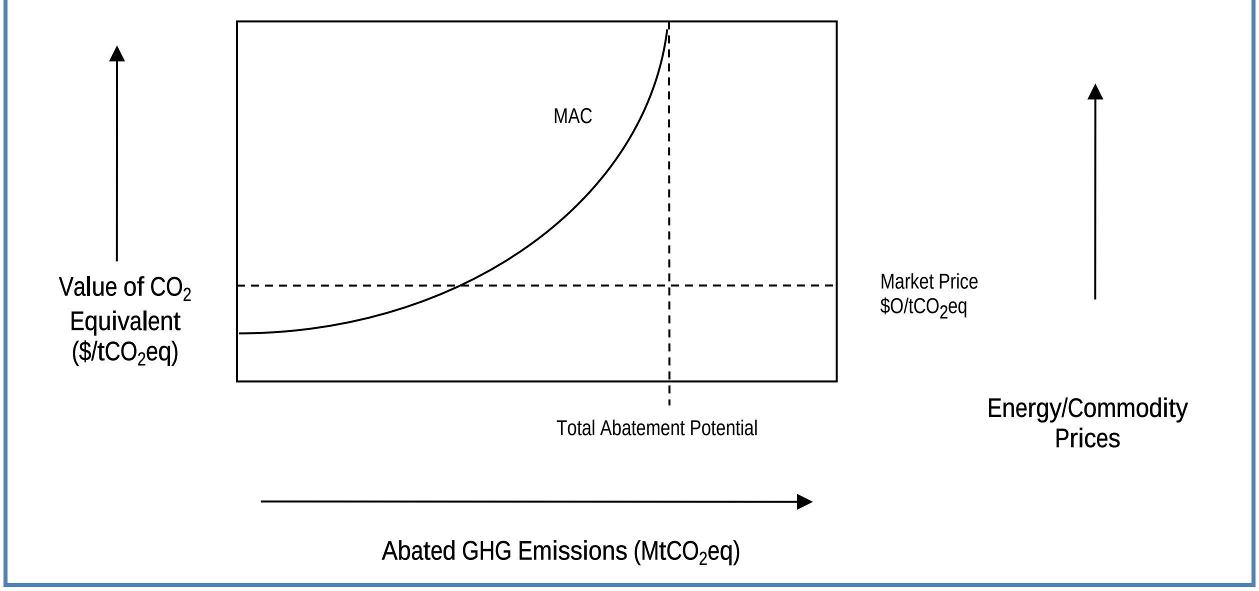
[a] Wage data was obtained primarily from U.S Bureau of Labor Statistics's International Labor Comparisons (BLS, 2010) and augmented with (BLS, 2010b), (BLS, 2010c) and (FSSS,2010).
[b] Energy Prices were obtained from EIA's *International Energy Statistics* (EIA, 2010b).
[c] Material factors were based on GDP/Capita statistics obtained from UNCTAD Statistical Database (UNCTAD, 2012).

Note that breakeven price calculations for this analysis do not include transaction or monitoring and reporting costs, because there are no explicit assumptions in this report about policies that would encourage and facilitate adoption of the mitigation options. Refer to Section I.5 for a more complete discussion of the limitations of this analysis.

I.3.3 Marginal Abatement Cost Curves

MACs are used to show the amount of emissions reduction potential at varying carbon price levels. In theory, a MAC illustrates the cost of abating each additional ton of emissions. Figure I-2 shows an illustrative MAC. The x-axis shows the amount of emissions abatement in $MtCO_2eq$, and the y-axis shows the breakeven price in $\$/tCO_2eq$ required to achieve the level of abatement. Therefore, moving along the curve from left to right, the lowest cost abatement options are adopted first.

Figure I-2: Illustrative Non-CO_2 Marginal Abatement Curve



The curve becomes vertical at the point of maximum total abatement potential, which is the sum of all technically feasible abatement options in a sector or region. At this point no additional price signals from GHG credit markets could motivate emissions reductions; any additional emissions reductions (shifting the vertical axis to the right) are due to increased energy efficiencies, conservation of production materials, or both.

The points on the MAC that appear at or below the zero cost line ($\$0/tCO_2eq$) illustrate potentially profitable mitigation options. These "below-the-line" amounts represent mitigation options that are already cost-effective given the costs and benefits considered (and are sometimes referred to as "no-regret" options) yet have not been implemented. However, there may be nonmonetary barriers that are preventing their adoption.

The MACs in this report are constructed from bottom-up average breakeven price calculations. The average breakeven price is calculated for the estimated abatement potential for each mitigation option (see Section I.). The options are then ordered in ascending order of breakeven price (cost) and plotted against abatement potential. The resulting MAC is a stepwise function, rather than a smooth curve, as seen in the illustrative MAC (Figure I-2), because each point on the curve represents the breakeven price point for a discrete mitigation option (or defined bundle of mitigation strategies).

Conceptually, marginal costs are the incremental costs of an additional unit of abatement. However, the abatement cost curves developed here reflect the incremental costs of adopting the next cost-effective mitigation option. We estimated the costs and benefits associated with all or nothing adoption of each well-defined mitigation practice. We did not estimate the marginal costs of incremental changes within each practice (e.g., the net cost associated with an incremental change in paddy rice irrigation). Instead, the MACs developed in this report reflect the average net cost of each option for the achieved reduction – hence the noncontinuous, stepwise nature of the curve.

In the energy and waste sectors, representative facilities facing varied mitigation costs employ mitigation technologies based on the lowest average breakeven option price. In calculating the abatement potential, options are evaluated according to whether they are complements or substitutes. If a group of options are complements (or independent of one another), the implied market shares are all equal to one. If options are substitutes for each other, then market shares that sum to one are used to distribute adoption across the available options (see table I.3). In some instances, the lowest price option is selected for each representative facility. When limited information is available, the market share is evenly distributed (1/n) across all viable options. In this way, the implied adoption rate for each technology is estimated.

In the industrial processes sector, mitigation options are applied to representative facilities, in order of lowest average breakeven price to highest average breakeven price. Each option is applied to a portion of the baseline emissions based on the implied adoption rate (the market share factor, as described in Section I.3.2.2), which, in the industrial sector, is informed by expert insight into potential adoption rates of various mitigation technologies.

In the agriculture sector, mitigation options are applied to the portion of emissions where they are technically applicable (e.g., anaerobic digesters are assumed to be applicable only in intensively managed dairy and hog production systems). The implied market share for competing options is based purely on the number of available migration options (n) that are applicable to a given subset of emissions and that reduce emissions[2] (1/n), where each option is applied to an equal portion of the cropland base or livestock population and, thus regional baseline emissions, for each region over time. Given the existence of nonprice and implementation factors that influence market share and the lack of accurate and detailed information regarding these qualitative characteristics, we assume an even distribution of options across the relevant baseline for the agriculture sector. This approach allows options to share a portion of market penetration, regardless of their cost-effectiveness, rather than allowing only the least-cost option to completely dominate the market. Our methodology is more conservative than if we had assumed only price factors exist, thus allowing the least-cost option to penetrate the sector by 100 percent.

The MACs represent the average economic potential of mitigation technologies in that sector, because it is assumed that if a mitigation technology is technically feasible in a given region, then it is implemented according to the relevant economic conditions. Therefore, the MACs do not represent the market potential or the social acceptance of a technology. The models used in the analysis are static (i.e., they do not represent adoption of mitigation technologies over time). This analysis assumes partial equilibrium conditions that do not represent economic feedbacks from the input or output markets. This analysis makes no assumptions regarding a policy environment that might encourage the implementation of mitigation options. Additional discussion of some key limitations of the methodology is provided in Section I.5.

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[2] Some agricultural mitigation options may increase emissions under certain conditions depending on baseline regional management and soil, climate, and other considerations. In addition, there are many mitigation options that increase emissions per head of livestock or per hectare of land, but reduce emissions intensity per unit of output. Thus, agricultural MACs are calculated both assuming constant production and constant area/head of livestock to present a range of potential mitigation. The options that provide net emissions reductions may differ between these alternative methods of MAC generation.

The end result of this analysis is a tabular data set for the MACs by sector, gas, and region, which are presented in Appendix A.[3] Sectoral MACs are aggregated by gas and by region to create global MACs, which are presented in Section I.4.2.

I.3.4 Methodological Enhancements from Analysis

This report builds on a study previously conducted by the USEPA for Stanford's EMF-21 and the USEPA (2006) report. The EMF-21 focused specifically on multigas strategies and the incorporation of non-CO_2 greenhouse gas data sets into economic models. Although this analysis is built largely on the previous USEPA analysis for the EMF-21, we have made several key enhancements.

New mitigation options have been added to the analysis for coal mining, agriculture, natural gas and oil systems sectors. This report also presents MAC curves for the domestic wastewater sector, flat panel display production, and photovoltaic cell production, which were not available in the previous report.

For industrial sources of fluorinated gases, the emissions baselines have been updated since the EMF-21 analysis. In addition, the MACs for aluminum manufacturing and electrical power systems have been enhanced with additional data.

The emissions baselines in the ODS substitute sector have also been enhanced. The EMF-21 ODS substitute baseline was an average between baselines derived by the USEPA and ECOFYS. For this report, the USEPA has generated an updated baseline. Assumptions in the ODS substitute sector, such as the market penetration potential of various mitigation options, have been updated from the EMF-21 analysis based on the input of industry experts.

In the agricultural sector, the previous methodology is improved on for this analysis by using updated versions of the biophysical, process-based models DAYCENT and DNDC that are utilized at a more spatially disaggregated level and with a more disaggregated set of baseline management types to which these options can be applied. These models capture the net greenhouse gas effects of the cropland and rice baseline emissions and mitigation options, and they reflect the heterogeneous emissions and yield effects of adopting mitigation practices. In addition, new agricultural mitigation options are now assessed, and more detailed results are provided for alternative baseline crop and livestock management practices.

I.4 Aggregate Results

Global total non-CO_2 greenhouse gas baseline emissions in 2010 are estimated at 11,389 MtCO_2e, and projected to increase 33% by 2030, totaling 15,157 MtCO_2e. Non-CO_2 anthropogenic emissions come from four major emitting sectors: the energy, waste management, industrial processes, and agricultural industries. China, United States, Russia, India and Brazil are the 5 largest country emitters and account for 40% of total emissions.

This section presents the projected baseline emissions for non-CO_2 anthropogenic greenhouse gases and provides a global overview of the MAC analysis results by sector and top emitting countries and regions from 2010-2030. The gases represented in the analysis are CH_4, N_20, and F-Gases[4], which are

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[3] Tables are presented that provide the percentage abatement for a series of breakeven prices. The MAC data are presented as tables so that exact values can be determined for use in modeling activities.

[4] F-Gases include fluorinated gases used as substitutes for Ozone Depleting Substances (ODS) and High-GWP gases from industrial processes (PFC, HFC-23, SF_6).

emitted from four major sectors: the agricultural, energy, waste, and industrial processes industries. China, the United States, the European Union, Brazil, and Russia are the world's five largest emitting countries as of 2010, accounting for 46 percent of total non-CO_2 emissions.

The data are aggregated in this chapter and provide a summary of all emitting sources and non-CO_2 greenhouse gases. The individual chapters are organized by source and present the full details of these analyses. For a complete set of mitigation potential by sector, gas, and region, refer to Appendix A.

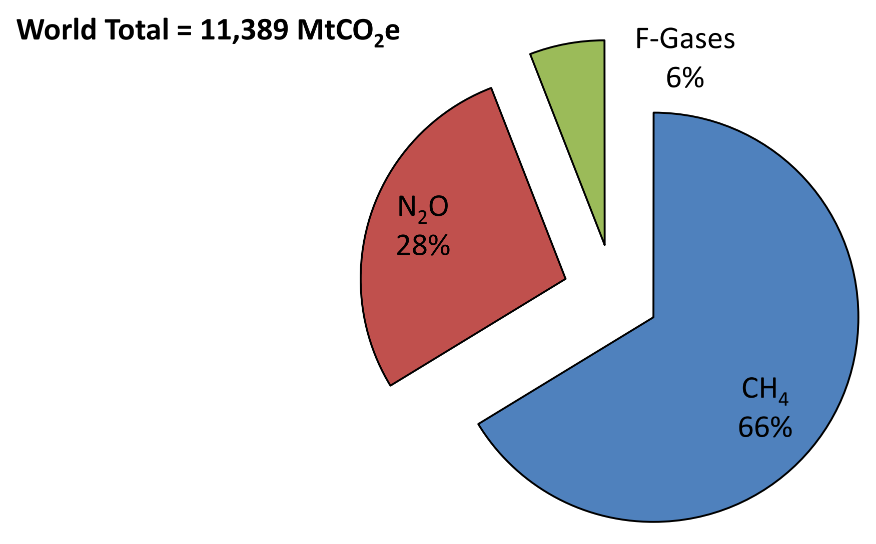
Baseline projections presented in this section come from the *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030* (USEPA, 2012). Since its publication there have been some minor revisions to the baseline projections for the industrial processes photovoltaic (PV) and flat panel display (FPD) manufacturing. The totals presented in this report will differ slightly from the projections in the 2012 report.

I.4.1 Baselines

By Non-CO_2 Greenhouse Gas

Figure I-3 illustrates the relative share of each non-CO_2 greenhouse gas that comprises the global baseline emissions total. CH_4 represents the largest share of emissions worldwide, accounting for approximately 66% of the total non-CO_2 greenhouse gas emissions in 2010, while N_2O and F-Gases account for the 28 percent and 6 percent, respectively.

Figure I-3: Percentage Share of Global Non-CO_2 Emissions[a] by Type of Gas in 2010

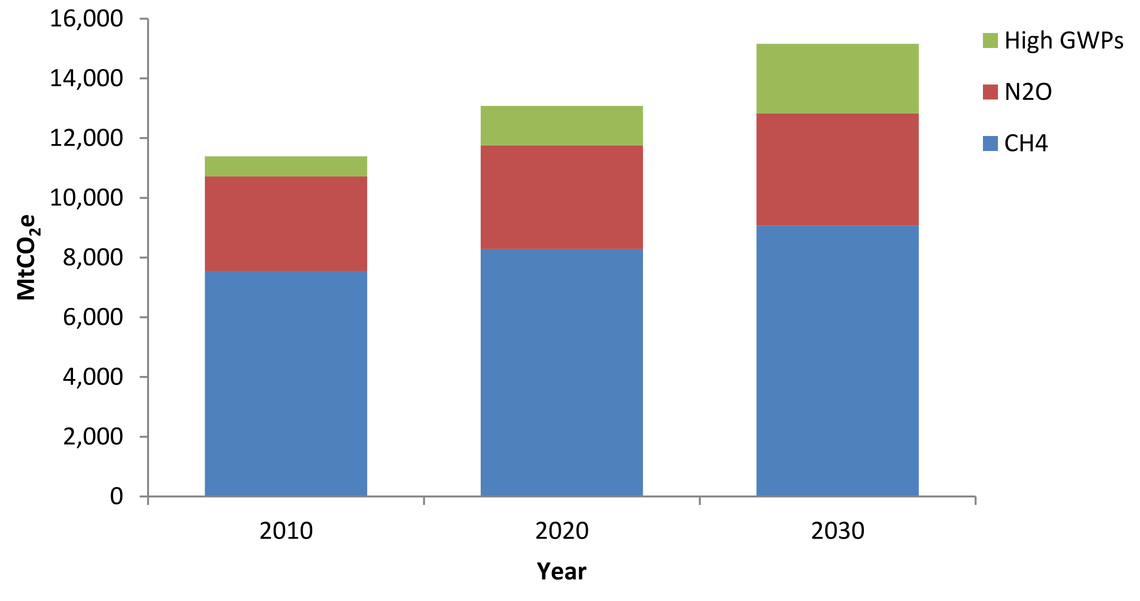


Source: USEPA, 2012.

[a] CO_2 equivalency based on 100-year GWP.

Figure I-4 presents the projected baseline emissions by greenhouse gas for 2010, 2020, and 2030. F-Gases represent the most significant change in baseline emissions. Accordingly to Figure I-4, high GWPs are to increase nearly 300 percent between 2010 and 2030. CH_4 and N_2O observe a more modest increase at an average decadal rate of roughly 10 percent. As a result, F-Gases are projected to gain 15 percent of the total share of non-CO_2 greenhouse gas emission by 2030, up from 4 percent in 2010

Figure I-4: Non-CO_2 Global Emissions Forecast to 2030 by Greenhouse Gas



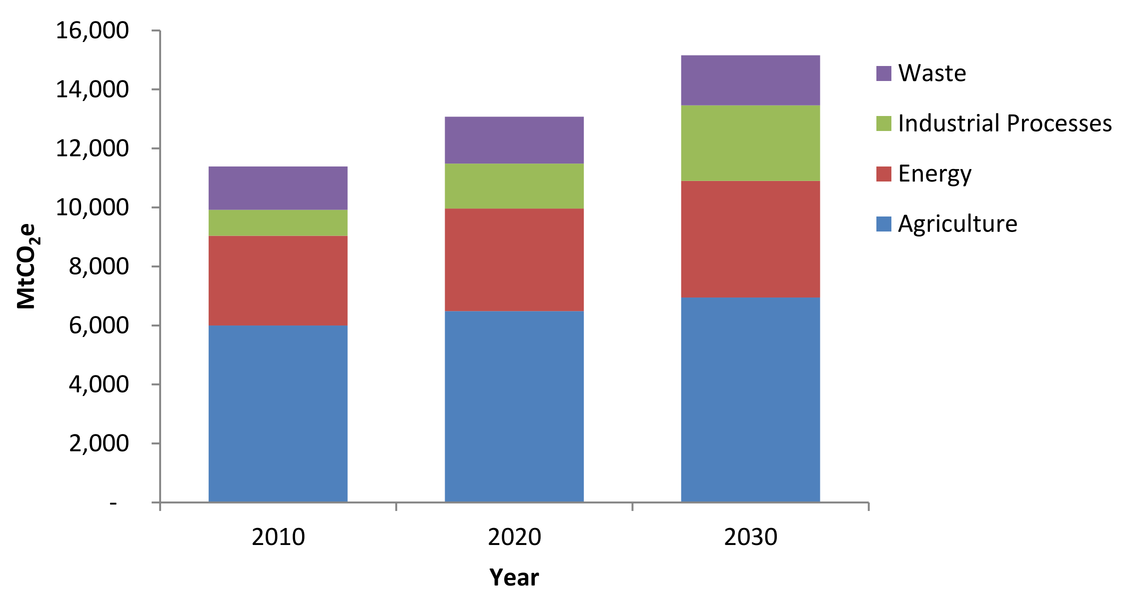
Source: USEPA, 2012.

By Major Emitting Sectors and Countries

The sources of non-CO_2 emissions are categorized into four major emissions sectors: energy, waste, industrial processes, and agriculture. Figures I-5 and I-6 provide the projected global baseline emission for 2010, 2020, 2030, by major emissions sector and by major emitting region, respectively. The agriculture sector includes soil and manure management, rice cultivation, enteric fermentation, and other nonindustrial sources such as biomass burning. Emissions sources categorized in the energy sector include coal mining activities, natural gas transmission and distribution, and gas and oil production. The waste sector includes municipal solid waste management, as well as human sewage and other types of wastewater treatment. The industrial processes sector includes a wide range of activities, such as semiconductor manufacturing, primary aluminum production, and electricity transmission and distribution.

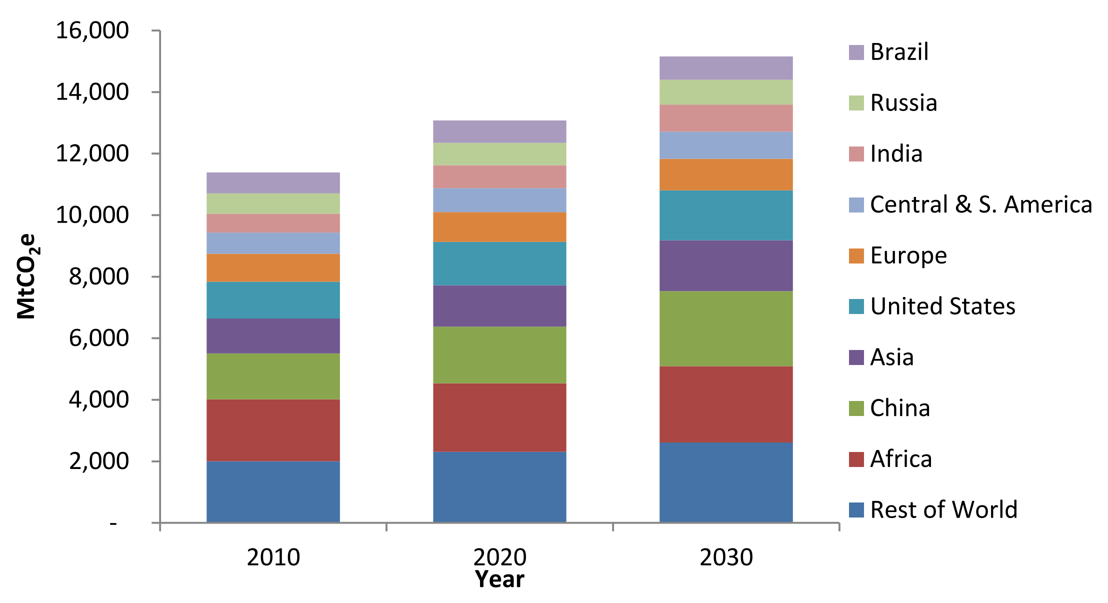
Agriculture is the primary source of non-CO_2 greenhouse gas emissions, accounting for 45 percent of the total 2010 baseline. Energy holds the second largest share of non-CO_2 emissions, representing 23 percent of the baseline. The waste and industrial processes sectors represent 11 and 7 percent, respectively. This trend will change through 2030, however, as emissions from the industrial processes sector is projected to increase by more than double, and will therefore produce more non-CO_2 emissions that waste by 2030.

Figure I-5: Global Emissions by Major Sector for all Non-CO_2 Greenhouse Gases



Source: USEPA, 2012.

Figure I-6: Projected World Emissions Baseline for Non-CO_2 Greenhouse Gases, Including Top Emitting Regions



Source: USEPA, 2012.

Figure I-6 shows the projected emissions baselines for the world, as well as the largest emitting countries. The largest non-CO_2 emitting countries are typically characterized as mature, highly industrialized countries or countries with significant agricultural industries. In 2010, the top five emitting countries – China, the United States, EU-15, Brazil, and Russia – account for 44% of the world's total non-

CO_2 emissions. Although 2010's top five emitting countries is projected to change during the next 20 years, their relative contribution to the world baseline will likely remain constant through 2030.

I.4.2 Global MACs

The MAC analysis methodology described in Section I.3 of this report develop bottom-up projections of potential reduction in non-CO_2 emissions in terms of the break-even price ($/t$CO_2$e). The emission reduction potential is constrained by the limitations of the technologies considered in the analysis, as well as regional and geographical applicability. In this report, MACs are developed for each major source by sector and country. The resulting series of MACs are aggregated up across sectors, gases and regions. The MACs indicate the potential reduction in non-CO_2 gas emissions for a given breakeven price. Figure I-7 presented the results from the MAC analysis for 2030 by major economic sector. Figure I-8 presents aggregate MACs by greenhouse gas type for 2030. Figure I-9 presents the 2030 MACs for the world's largest non-CO_2 greenhouse gas emitting regions.

Figure I-7: Global 2030 MACs by Non-CO_2 Greenhouse Gas

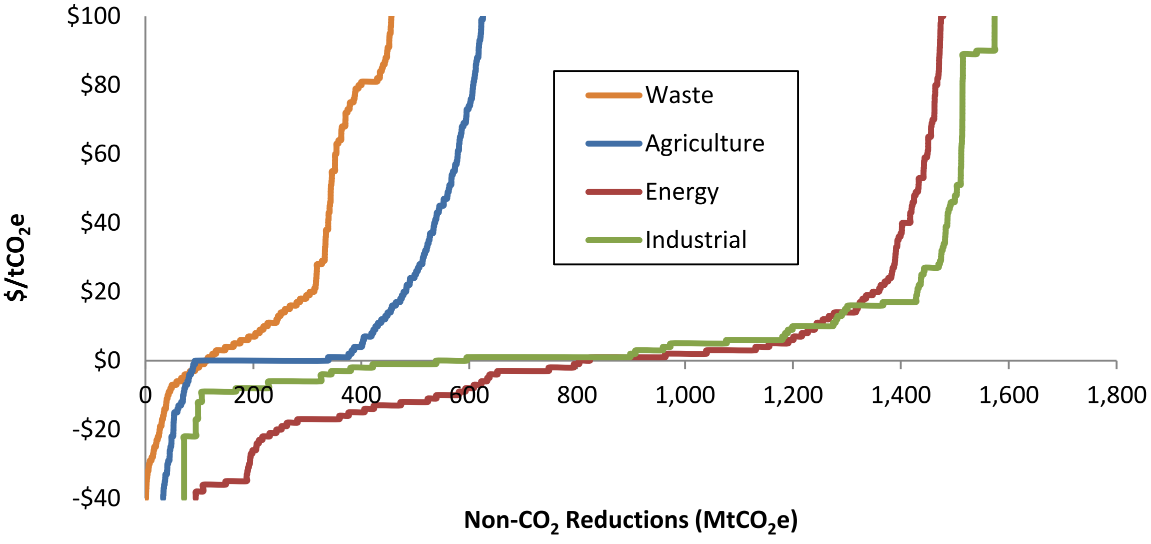


Figure I-8: Global 2030 MACs for Non-CO_2 Greenhouse Gases by Major Emitting Regions

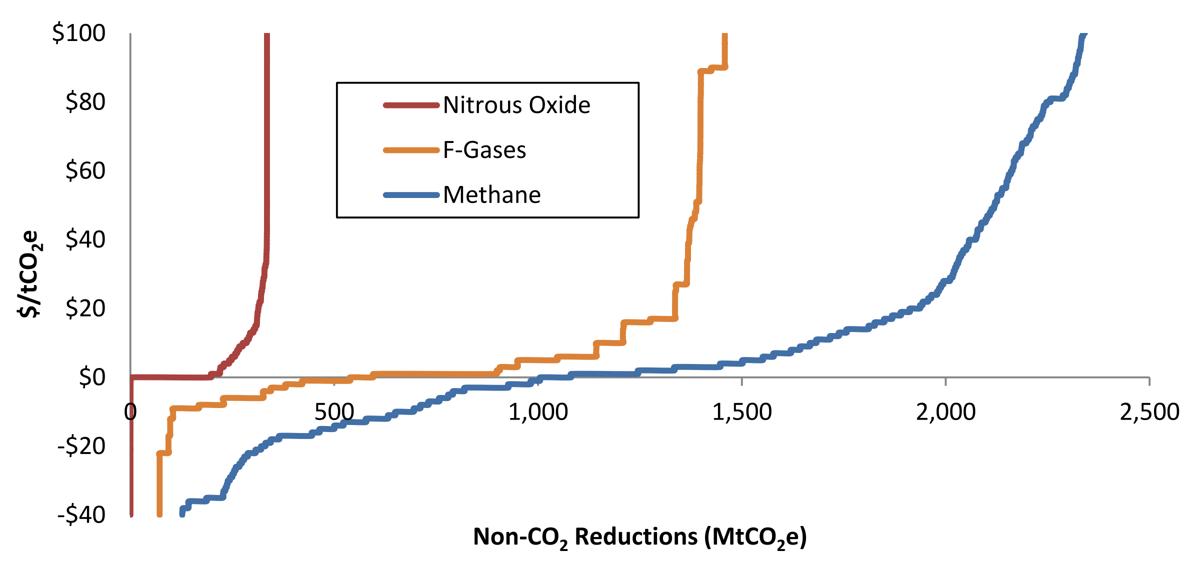
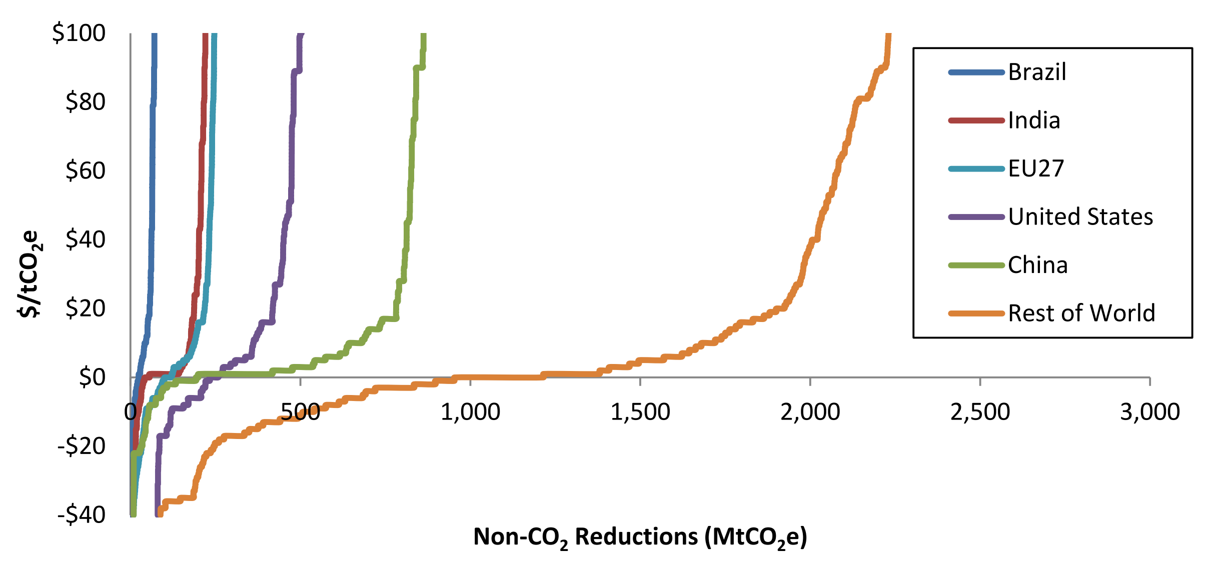


Figure I-9: Global 2030 MACs for Non-CO_2 Greenhouse Gases by Major Emitting Regions



I.5 Limitations and Uncertainties

The results of this analysis cover the major emitting regions, emissions sources, and abatement options; we discuss a few limitations of this analysis briefly below.

I.5.1 Exclusion of Transaction Costs

Ongoing work in the area of mitigation costs continues focus on including transactions costs. As discussed in the 2006 version of this report, Lawrence Berkeley National Laboratory (LBNL), *Assessing Transaction Costs of Project-based Greenhouse Gas Emissions Trading* (Antinori and Sathaye 2007), which reported that transactions costs range between $0.03 per metric ton of carbon dioxide for large projects to $4.05 per ton of carbon dioxide for smaller projects, with a weighted average of $0.36 per tonne of carbon dioxide for a suite of projects considered. More recent MAC work by others (Rose, et al. 2013) estimated the unit cost of an abatement project increases by an average of 15% when transaction costs are included. Transaction costs vary significantly, contingent on the size of the project, the applicable mitigation technology, and other factors. Given the lack of comprehensive data, this analysis continues to exclude transaction costs from the analysis.

I.5.2 Static Approach to Abatement Assessment

This 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 2030 and an option's parameters are not changed over its lifetime. This current limitation likely underestimates abatement potential 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 a better representation of how MACs change over space and time. Developing more dynamic MACs to capture the impacts of technological change should be included in any future MAC development.

I.5.3 Limited Use of Regional Data

The analytic framework used in this study is flexible enough to incorporate regional differences in all the characteristics of abatement options. However, a lack of country-specific data led to a reliance on expert judgment, as noted in the sector-specific chapters. This expert judgment 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 judgment, because the makeup 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 CH_4 abatement in countries outside the United States and EU. Incorporating more regional data could also enhance the range of emissions sources and mitigation options addressed in this analysis.

I.5.4 Exclusion of Indirect Emissions Reductions

This analysis does not account for indirect emissions reductions, which can result from either the substitution of electricity from the grid, with electricity produced on-site from recovered CH_4, or from the substitution of natural gas in pipelines with recovered CH_4. Calculation of such indirect reductions requires additional assumptions about the carbon intensity of electricity in different regions. In the U.S. landfill sector, indirect reductions generally augment emissions reductions by about 15 percent. In the agricultural sector, although some mitigation options primarily target a single gas, implementation of the mitigation options will have multiple greenhouse gas effects, most of which are reflected in the agricultural results.

References

Antinori, C. and J. Sathaye 2007. *Assessing Transaction Costs of Project-based Greenhouse Gas Emissions Trading.* Lawrence Berkeley National Laboratory (LBNL). Report No. LBNL-57315.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel for Climate Change (IPPC). 1996. *IPCC Guidelines for National Greenhouse Gas Inventories.* Three volumes: Vol. 1, Reporting Instructions; Vol. 2, Workbook; Vol. 3, Reference Manual. Paris, France: Intergovernmental Panel on Climate Change, United Nations Environmental Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Rose, S.K., R. Beach, K. Calvin, B. McCarl, J. Petrusa, B. Sohngen, R. Youngman, A. Diamant, F. de la Chesnaye, J. Edmonds, R. Rosenzweig, and M. Wise, 2013. *Estimating Global Greenhouse Gas Emissions Offset Supplies: Accounting for Investment Risks and Other Market Realties.* Electric Power Research Institute [EPRI], Palo Alto, CA. Report 1025510.

Russian Federation Federal State Statistics Service (FSSS), 2010. *Main Indicators: Living Standards*. Table 7.7: Average Monthly Nominal Accrued Wages of Employees of Organisations by Kinds of Economic Activities. 2010. http://www.gks.ru/bgd/regl/b10_12/IssWWW.exe/stg/d01/07-07.htm

United Nations Conference on Trade and Development (UNCTAD). 2012. *National Accounts: Nominal and Real GDP, total and per capita, annual 1970-2011*. UNCTAD Statistical Database. Available at: http://unctadstat.unctad.org.

U.S. Bureau of Labor Statistics (BLS), 2010a. *International Comparisons of Hourly Compensation Costs in Manufacturing, 1996-2008*. Table 8: Production Workers: Hourly Compensation Costs in U.S. Dollars in Manufacturing, 33 countries or areas and selected economic groups, 1975-2008; and Table 2: All Employees: Hourly Compensation Costs in U.S. Dollars in Manufacturing, 33 countries or areas and selected economic groups, 1996-2008 Released August 26, 2010. http://www.bls.gov/fls/.

U.S. Bureau of Labor Statistics (BLS), 2010b. "Labor costs in India's organized manufacturing sector." Table 2: Hourly compensation costs in India's organized manufacturing sector, 1999–2005. May 2010. http://www.bls.gov/opub/mlr/2010/05/art1full.pdf.

U.S. Bureau of Labor Statistics (BLS), 2010c. "Manufacturing in China." Table 1: Hourly compensation costs of manufacturing workers in China, 2002-2008." October 27, 2010. http://www.bls.gov/fls/china.htm#data_comparability.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

U.S. Department of Energy's Energy Information Administration (EIA), 2010a. *International Energy Statistics.* Electricity Prices for Industry. June 10, 2010. http://www.eia.gov/emeu/international/elecprii.html

U.S. Department of Energy's Energy Information Administration (EIA), 2010b. *International Energy Statistics.* Natural Gas Prices for Industry. June 10, 2010. http://www.eia.gov/emeu/international/ngasprii.html.

II. Energy Sector

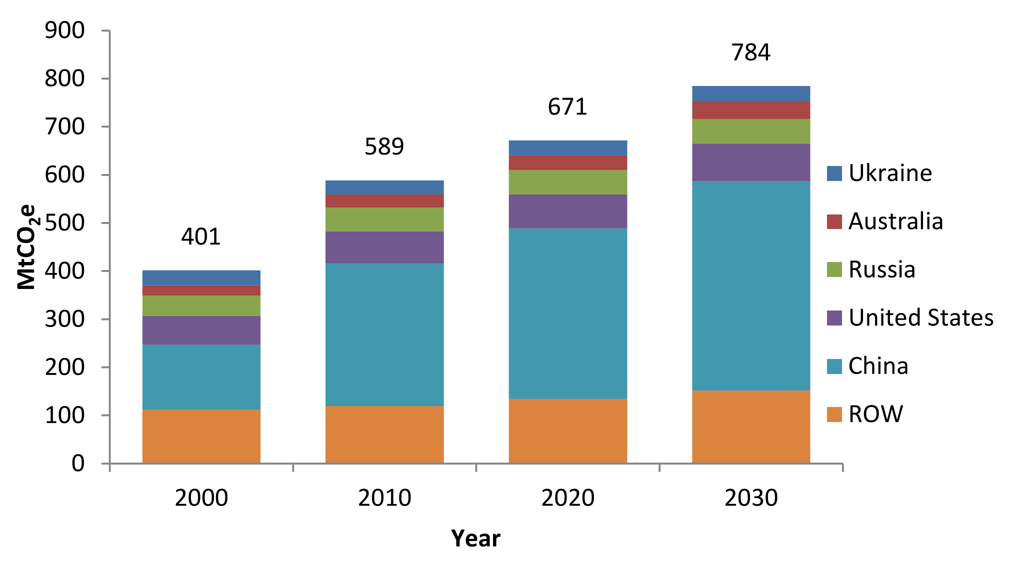
II.1. Coal Mining

II.1.1 Sector Summary

Coal mining is a significant source of anthropogenic GHG emissions. Coal is an important energy resource in many of the world's economies, used for energy generation or as a feedstock in industrial production processes. Extracting this energy resource through underground and surface mining releases methane (CH_4) stored in the coal bed and surrounding geologic strata. The U.S. Energy Information Administration's (USEIA's) (2011) most recent international energy outlook projects a 39% increase in coal production between 2010 and 2035, reflecting continued economic and industrial development of the world's emerging economies. In the absence of widespread adoption of abatement measures by the coal mining sector, expanding coal production to meet growing energy demands will subsequently lead to increases in anthropogenic emissions.

Worldwide, the coal mining industry liberated more than 589 million metric tons of carbon dioxide equivalents ($MtCO_2e$), which accounted for 8% of total anthropogenic CH_4[1] emissions in 2010. The top 5 emitting countries of China, the United States, Russia, Australia, and Ukraine account for more than 80% of coal mining CH_4 emissions. Figure 1-1 summarizes the business-as-usual (BAU) emission baselines for the coal mining sector. By 2030, emissions levels are projected to more than double the levels in 2000. The most rapid period of emissions growth occurred in the first decade of this century. More measured growth is projected beyond 2010. Between 2010 and 2030, emissions are projected to grow by 33%. Currently, China represents over 50% of global emissions. China's share of global emissions is projected to increase to 55% by 2030.

Figure 1-1: CH_4 Emissions from Coal Mining: 2000–2030



Source: U.S. Environmental Protection Agency (USEPA), 2012.

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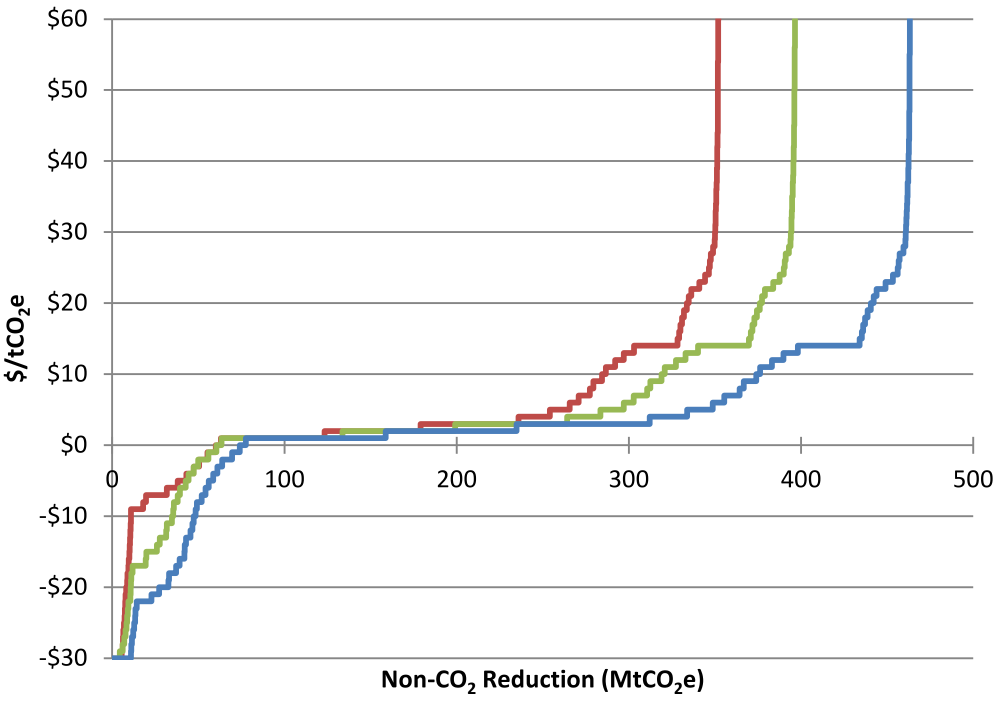
[1] Global CH_4 in 2010 = 7,549.2 $MtCO_2e$ (see Table A-2 in USEPA, 2012)

Capture for use or destruction are two alternative abatement measures that can mitigate CH_4 emissions associated with underground mining. For mines that are able to utilize the recovered gas, the captured methane represents a potential revenue stream that may offset a portion of the cost of implementing the abatement measure. Specifically, three categories of abatement measures are considered: (1) gas recovery for energy end uses; (2) combustion through flaring; and (3) ventilation air methane (VAM) recovery and destruction through thermal or catalytic oxidation, where low concentrations of CH_4 present in ventilation air exhaust flows are oxidized.

Global abatement potential that is technologically achievable from underground coal mining based on the abatement measures considered is approximately 60% of total annual emissions in 2030. Marginal abatement cost (MAC) curve results are presented in Figure 1-2 for 2010, 2020, and 2030. Maximum abatement potential in the coal mining sector is 400 and 468 $MtCO_2e$ in 2020 and 2030 respectively.

Figure 1-2: Global Abatement Potential in Coal Mining: 2010, 2020, and 2030



While maximum abatement could only be achieved at higher carbon prices, the MAC results suggest that significant opportunities for CH_4 reductions in the coal mining sector at carbon prices at or below $10. Furthermore there are approximately 78 $MtCO_2e$ of reductions that are cost-effective at currently projected energy prices. These reductions are sometimes referred to as no-regret options.

The following section offers a brief explanation of how CH_4 is emitted from coal mines, followed by a discussion of projected trends in international baseline emissions. Section II.1.3 characterizes possible abatement technologies, outlining their technical specifications, costs and possible benefits, and potential in selected countries. The final section of this chapter discusses emissions reductions that occur following the implementation of each abatement technology and how these reductions are reflected in the MACs.

II.1.2 Methane Emissions from Coal Mining

Methane is produced during a natural process that converts organic material into coal. Methane is stored in the coal through a physical process referred to as sorption. Sorbed methane is condensed within the matrix of the coal as long as the hydrostatic pressure is maintained, but during the mining process, the pressure drops and the gas will begin to desorb and flow into the mine's workings. Methane is also stored in the free spaces of the coal strata and migrates to the mine workings. Many factors affect the quantity of CH_4 released, including the gas content of the coal, the permeability and porosity of the coal seams, the method of mining used, and the production capacity of the mining operation. The concentration of methane present in the coal seam depends on several factors but generally increases with depth. There are four major sources of CH_4 emissions in the coal sector including underground mines, surface mines, post-mining processing, and abandoned mines. Underground mining is the largest single source of emissions in the sector.

Underground Mines. High concentrations of CH_4 in underground coal mines is a safety hazard. Mines are ventilated by use of large fans which are capable of moving large volumes of air through the active workings. Air is drawn across the working face, where coal is being extracted, and exhausted to the atmosphere. This is often adequate to maintain safe levels of methane in the mine workings.

In especially gassy mines, the ventilation system may be supplemented by degasification systems, to ensure adequate evacuation of methane from the mine to ensure safe working conditions. Degasification systems are necessary to ensure safe operations in highly gas prone underground mines that are susceptible to gas outbursts and high methane emissions encountered at the mining face. The primary methods to reduce emissions at the mining face include pre-mine drainage systems that reduce the methane pressure in the coal seam, thereby reducing both the total volume of methane emitted at the mining face and the rate at which it is emitted and post-mining boreholes which drain methane from the collapsed and fractured zone (gob) behind the mining face. These reduce the concentration of methane, especially near the active mining coal face.

Degasification systems consist of a network of boreholes drilled from the surface, or within the mine for the purpose of removing CH_4 before, during, or after mining. These wells extract coal mine methane from the coal seam at relatively high concentrations (30% to 90%). Concentrations vary depending on the type of coal mined and the degasification technique used. In contrast, underground mine ventilation systems emit large quantities of very dilute methane (typically less than 1% methane), known as "ventilation air methane" or VAM.

Traditionally, CH_4 extracted from the mine is released or vented into the atmosphere. It is possible to mitigate underground mine methane emissions, especially from degasification systems, by capturing the gas and either flaring it or recovering and using it for energy. In the case of VAM, the relatively low CH_4 concentration makes it more challenging both technically and economically to mitigate it or recover energy from it.

Surface Mines**.** Surface mining is a technique used to extract coal from shallow depths at or below the Earth's surface. Because the hydrostatic pressure at shallow depths is lower, the in situ CH_4 content is not as high at surface mines as at underground mines. CH_4 emissions from surface mines (expressed as volume of CH_4 per mass of coal mined) are typically less than from underground mines. As the overlying soil and rock is removed and the coal exposed, CH_4 is emitted directly into the atmosphere. Both because of its lower methane contents and because surface mining is only applicable in certain geographic regions, surface mines may contribute only a small fraction of a country's overall emissions. For example, in the United States in 2009, surface mining accounted for over 60% of coal production, while only accounting for 18% of CH_4 emissions from coal mining (USEPA, 2011b). In China, there is very little surface mining whereas in India almost all coal production is from surface mines. The only technically feasible abatement measures available to surface mining are pre-mine methane drainage in advance of mining, similar to coal bed methane (CBM) recovery operations (USEPA, 2008a), or horizontal boreholes into a high wall where the operation starts as a surface mine but eventually the drift requires the operation to become an underground mine. Given the limited contribution surface mines make to national baseline emissions, this analysis did not consider any abatement measures for surface mining.

Post-mining Operations. Following the mining operations, a series of operations, called *post-mining operations*, constitutes a third source of CH_4 emissions. Not all CH_4 gas is released from coal during the process of coal breakage that takes place during extraction and transport to the surface at mining operations; some emissions occur during the processing, storage, and transport of coal as the coal continues to de-gas. The rate of post-mining emissions depends on the rank of coal and the way it is handled. The highest rate of emissions occurs when coal is crushed, sized, and dried for industrial and utility uses. Given the limited contribution of post-mining emissions to national baseline emissions and the limited technical options to abate these emissions from rail cars or storage piles, this analysis does not consider any abatement measures for post-mining operations.

Abandoned Mines. Abandoned mines are another source of CH_4 emissions. Emissions are released through old wells, ventilation shafts, and cracks and fissures in overlying strata. In some cases, the CH_4 from these mines has been captured and used as a source of natural gas or to generate electricity. The 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines provide a separate methodology for reporting emissions from abandoned coal mines. Hence, emissions from this source are excluded from this analysis and are not included in the baseline estimates. Although there are abatement options for recovering and using methane from abandoned mines, these options were not examined in this analysis.

In summary, the majority of the CH_4 emitted from coal mining operations comes from gassy underground mines via ventilation systems and degasification systems. Smaller, but still significant, amounts of CH_4 are emitted from surface mining and post-mining operations and from abandoned mines. Future levels of CH_4 emissions from coal mining, however, will be primarily determined by the management of CH_4 gas at active underground mines.

II.1.2.1 Activity Data and Related Assumptions

Globally, coal production is expected to increase by 39% from 2010 to 2035, growing at an average annual rate of 1.8%. Future baseline CH_4 emissions estimates are directly related to projections of future levels of coal production. Projected coal production is based on global trends in the demand and supply of coal, which are particularly influenced by the global mix of electricity generation sources. China and India are expected to account for 72% of the increase in global production as they try to meet their demand with domestically produced coal (USEIA, 2011).

Three quarters of the world's recoverable coal reserves are located in five countries: the United States (27%), Russia (18%), China (13%), Australia (9%), and India (7%) (USEIA, 2011). Because global coal consumption is projected to increase over the next several decades, it is also expected that these five countries will produce the majority of coal to meet the demand. Efforts in recent years by China to modernize its coal mining operations are allowing coal to be mined at greater depths and at lower cost. This, combined with a tremendous demand for coal-generated electricity, has contributed to substantial increases in CH_4 emissions.

Emissions factors for coal mining vary depending on the type of coal being mined, the depth at which the mining face is located, and how much coal is being produced in a given year. These factors also vary across countries and time. Emissions factors are estimated for each country and are based on the methodologies detailed in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The IPCC guidelines provide a methodology for countries developing emissions factors based on the availability and certainty of emissions data.[2] Table 1-1 reports IPCC Tier 1 emissions factors for underground mines based on CH_4 intensity and coal seam depth unadjusted for any CH_4 utilization or flaring.

Table 1-1: IPCC Suggested Underground Emissions Factors for Selected Countries in m^3/tonne Coal Produced

Tier 1—CH_4 Emissions Factor	Emissions Factor (m^3/tonne)	Emissions Factor[a] (tCO_2e/tonne)
Low (< 200m)	10	0.14
Average	18	0.26
High (> 400m)	25	0.36

Source: IPCC, 2006. Chapter 4: Fugitive Emissions in *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 2. Energy.* Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

[a] Conversion factor of 1 $m^3 = 0.0143\ tCO_2e$

Improvements made in mining technology throughout the last 30 years have resulted in the ability to extract coal from increasingly greater depths. Developing countries' adoption of advanced mining technology has allowed countries such as China and Russia to reach deeper into their existing coal reserves. As noted earlier, the volume of CH_4 in the coal seam may increase at greater depths because of increasing hydrostatic pressure. Thus, it is expected that the CH_4 emission factors will increase as technology allows large coal-producing countries to mine deeper, gassier coal seams.

II.1.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emissions trends and presents the baseline emissions used in the MAC analysis.[3]

Historical Emissions Estimates

Global CH_4 emissions from coal mining increased by 14% between 1990 and 2010. Key factors that contributed to the emissions growth over this time period include overall increases in coal production as well as technological improvements that have enabled coal mining at increased depths. For additional detail on historical emissions estimates we refer the reader to USEPA's *Global Emissions Report* (2012).

Projected Emissions Estimates

Absent the widespread adoption of abatement technologies, worldwide global CH_4 emissions from coal mining will continue to increase at an accelerated rate. Over the next 20 years, emissions are expected to grow at an average annual rate of 1.5%, compared with 0.07% between 1990 and 2010. The projected increase is driven by a number of factors, including continued mining technology advances and increasing demand for coal for electricity production over the same period. Large, increasingly developed countries, such as China and India, are expected to experience high levels of economic growth. Economic

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[2] Emissions factors for underground mines, the largest source of CH_4 emissions from coal mining, are the same as those described in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, and emissions factors for surface mines, post-mining, and abandoned mines are all based on the IPCC's 2006 guidelines.

[3] For more detail on baseline development and estimation methodology, the authors refer the reader to the USEPA's *Global Emissions Projection Report* available at: www.epa.gov/climatechange/economics/international.html.

growth in these countries will be the biggest driver of future CH_4 emissions from coal mining. Increasing rates of technological adoption and modernization of mining operations will allow developing countries to mine deeper and more effectively and, in turn, produce more CH_4 emissions. Table 1-2 presents baseline emissions projections by country and region from 2010 to 2030.

Table 1-2: Projected Emissions from Coal Mine CH_4 by Country and Region: 2010 to 2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	296	321	354	397	436	2.0%
United States	67	70	70	73	78	0.7%
Russia	49	51	51	50	51	0.3%
Australia	27	30	31	34	37	1.5%
Ukraine	30	31	31	31	31	0.3%
Rest of World (ROW) by Region[b]						
Africa	10	11	11	12	12	1.1%
Central & South America	9	11	13	14	16	3.0%
Middle East	0	0	0	0	0	3.5%
Europe	30	29	29	29	29	−0.2%
Eurasia	22	23	23	23	24	0.3%
Asia	45	49	55	61	67	2.0%
North America	3	3	3	3	3	−0.7%
World Total	**589**	**630**	**671**	**725**	**784**	**1.4%**

[a] CAGR = Compound Annual Growth Rate

[b] ROW by Region excludes emissions from top 5 countries.

Source: USEPA, 2012

II.1.3 Abatement Measures and Engineering Cost Analysis

This analysis considers five abatement measures classified into three technology categories that include recovery for pipeline injection, power generation or use as a process fuel/on-site heating, flaring, and catalytic or thermal oxidation of VAM. It should be noted that mitigation of gas from degasification systems and ventilation systems are independent of each other. Abatement measures in the coal mining sector consist of one or more of the following primary components: (1) a drainage and recovery system (where applicable) to remove methane from the coal seam pre-mining or from the gob area post mining, (2) the end-use application for the gas recovered from the drainage system (where applicable), and (3) the ventilation air methane recovery or mitigation system (where applicable).

Costs are derived from USEPA's Coalbed Methane Outreach Program (CMOP) project Cash Flow Model (USEPA, 2011b) and applied to a representative population of underground mines. Table 1-3 summarizes the average total installed capital costs and annual operations and maintenance (O&M) costs for each abatement measure.

Table 1-3: Summary of Abatement Measures for Coal Mines

Abatement Measure	Total Installed Capital Cost[a] (million USD)	Total Annual O&M Cost (million USD)	Technical Lifetime (Years)	Technical Effectiveness[b] (%)
Energy End Uses				
Pipeline injection	8.4	2.4	15	21%
On-site electricity generation	23.0	2.6	15	28%
On-site use for process heat	2.8	1.2	15	28%
Excess Gas Flaring				
Enclosed flare system	2.3	1.5	15	28%
Mitigation of VAM				
VAM oxidation	8.0	1.3	15	19–68%

[a] Capital costs include costs of both recovery and abatement equipment requirements.

[b] Abatement potential expresses the maximum potential emission reductions at a facility level.

This section describes the abatement measures and associated costs of the methane recovery and abatement in the coal mining sector. Each technology is briefly characterized followed by a discussion of costs, potential benefits, technical effectiveness, and applicability assumptions used to estimate the abatement potential.

Technical effectiveness factors are calculated by considering a number of technological efficiency and applicability factors. Table 1-4 presents these factors for each abatement measure. These include the technical effectiveness of the recovery system and reduction efficiency of the utilization or destruction technology. Technical effectiveness, represented by [E] in Table 1-4, of any option at the mine level is equal to the product of the facility applicability, recovery efficiency, technical feasibility, and reduction efficiency factors.

Table 1-4: Factors Used to Estimate Abatement Potential in Coal Mines

Abatement Measure	Facility Applicability [A]	Recovery Efficiency [B]	Technical Feasibility [C]	Reduction Efficiency [D]	Technical Effectiveness [E]
Energy End Uses: Drained Gas					
Pipeline injection	38%	75%	100%	75%	21%
On-site electricity generation	38%	75%	100%	98%	28%
On-site direct use	38%	75%	100%	98%	28%
Mitigation only: Drained gas					
Enclosed flare system	38%	75%	100%	98%	28%
Oxidation of VAM					
VAM oxidation	62%	25% - 90%	77%	98%	19–68%

$Technical\ Effectiveness\ [A] \times [B] \times [C] \times [D] = [E]$

Facility applicability [A] represents the share of total mine-level methane emissions that are available for abatement through degasification and VAM. Approximately one-third[4] of total mine emissions can be recovered through degasification (also commonly referred to as drainage), while the majority of mine emissions are released at low concentrations in the ventilation air referred to as VAM.

Recovery efficiency [B] relates to the collection system (see Section II.1.3.1) itself and reflects what may be recovered through the drainage wells or ventilation exhaust systems. Only a fraction of the total drained CH_4 may be effectively used or destroyed because of natural variances in the volume and concentration of methane collected. With respect to VAM oxidation, for this analysis recovery efficiency is set at 25% in 2010 and grows to 90% by 2030.

Technical feasibility [C] relates to the physical or technical limitations of the technologies. It is technically feasible to safely combust mine gas with CH_4 concentrations greater than 30% for drained gas or 0.25% for VAM. A value of 77% for VAM represents the fraction of exhaust vents with methane concentrations high enough (>0.25%) to allow for oxidation.[5] Finally, the reduction efficiency [D] is the factor that describes the destruction efficiency of each end use or combustion technology. For pipeline injection, the reduction efficiency represents the methane losses that occur during transport from the mine to the point of sale into a natural gas pipeline.

II.1.3.1 Methane Recovery System from Degasification/Drainage Systems

High-quality CH_4 is recovered from coal seams by drilling vertical wells from the surface up to 10 years in advance of a mining operation or drilling in-mine horizontal boreholes several months or years before mining. Most mine operators exercise just-in-time management of gate road development; subsequently, horizontal cross-panel boreholes are installed and drain gas for 6 months or less (USEPA, 2011b).

The components of the capital and annual costs for the drainage wells are outlined as given in USEPA's CMOP Cash Flow Model documentation (USEPA, 2011b). The recovery system includes the equipment required for drainage wells, gas gathering lines, and delivery systems for coal mine methane (CMM). The recovery system is included in the costs of all abatement measures with the exception of VAM oxidation.[6] These costs are additive to the costs associated with each abatement measure.

- **Capital Cost:** The capital costs for a drainage system are a function of the recovered gas flow rate. Equipment requirements include construction of the drainage well(s), a wellhead blower, a satellite compressor station, and gathering pipelines that connect the compressors to the methane end-use technology. The total installed capital costs will vary by location and gas flow rate. For example, assuming a 600 Mcf/day volume of CMM gas (with a CH_4 concentration of 90%), we estimate the capital costs would be $850,000. See Appendix B for additional detail on equipment cost assumptions.

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[4] The proportion of mine CH_4 emissions recoverable through degasification systems can vary from 0% to 70% depending on the gassiness of the mine. This analysis uses 38%, which represents an average for gassy mines.

[5] This value may be a high estimate based on anecdotal evidence from field testing experience. For example, the number of mines in Asia that meets a threshold for application of available and field-tested VAM abatement systems is much lower.

[6] A recovery system is not required for VAM oxidation because it relies on the mine's existing ventilation system that would be installed before mining operations commence.

- **Annual Operating and Maintenance (O&M) Costs:** The annual costs are required to maintain the drainage system equated to approximately $2.2/Mcf per year. These costs include the ongoing installation of gob wells and the gathering system piping that connects the wells to satellite compressors. In keeping with the example mine of 600 Mcf/day, the annual O&M costs associated with the recovery system would be approximately $475,000.
- **Recovery Efficiency:** Recovery efficiency is assumed to be 75%.

II.1.3.2 Degasification for Utilization in Energy Production

This category of abatement measures includes (1) recovery for pipeline injection and (2) recovery for electricity generation. Both options require a recovery system in place to extract the methane gas from the coal seams. Which technology is most cost-effective will be determined by a combination of regional energy prices and the capital equipment requirements.

Degasification for Pipeline Injection

Natural gas companies may purchase CH_4 recovered from coal mines. CH_4 suitable for sale into natural gas pipelines must have a concentration of at least 96% and contain no more than 4% concentration of noncombustible gases with a maximum of 4% carbon dioxide or nitrogen and 1 ppm oxygen. Although CH_4 from coal mines requires water removal, it is typically free of hydrogen sulfide and other impurities found in natural gas. Hence, little to no additional treatment and processing are necessary to meet the requirements for pipeline injection. In some cases, high-quality CH_4 also can be obtained from gob wells.

Premining degas wells are the preferred recovery method for producing pipeline quality CH_4 from coal seams because the recovered methane is not contaminated with ventilation air from the working areas of the mine.

Gob wells, in contrast, generally do not produce pipeline-quality gas because the methane is frequently mixed with ventilation air. Gob gas CH_4 concentrations can range from 30% to over 90%. It is possible to upgrade gob gas for pipeline quality although blending with pre-mine drained gas and/or oxygen removal may be necessary, adding to the cost of gas processing. However, it is possible to maintain a higher and more consistent gas quality through careful monitoring and adjustment of the vacuum pressure in gob wells as has been demonstrated in the United States (USEPA, 2008b).

The viability of a pipeline project is affected by several key factors. First is a coal mine's proximity to a commercial pipeline. The cost of constructing a pipeline to connect to a commercial pipeline can vary greatly depending on distance. Secondly, and more importantly, the terrain will affect the viability of a commercial pipeline project. Many mining areas are located in hilly and mountainous regions, thus increasing the difficulty and cost of constructing both gathering lines and pipeline to connect to the commercial natural gas pipeline (USEPA, 2008b). Finally, disposal of water produced from vertical wells may be a significant factor in determining the economic viability of a pipeline project.

- **Initial Capital Cost:** The per facility installed capital costs for pipeline injection of gob gas, as described in USEPA (2011b), include the installation of a pressure swing adsorption system to remove nitrogen and carbon dioxide down to a 4% inert level. The utilization cost is a function of both the inlet gas flow rate and methane concentration and includes the cost of dehydration and compression necessary to process the gas and boost the sales gas to pressure for injection in a natural gas transmission pipeline. While there may be a range of pressures at which pipelines operate, this analysis assumes an operating pressure of 900 psig. This option also includes the installation of a catalytic oxygen removal system and a pipeline to connect the mine's gas processing system to a natural gas pipeline. Pipeline costs estimated for this analysis are adjusted based on mine proximity to commercial pipeline but do not attempt to account for variations in terrain across countries.

- **Annual O&M Costs:** The annual costs include costs of recovery system and cost of gas treatment and compression required for injection into commercial natural gas pipelines.
- **Annual Benefits:** Revenues from this option are the gas sales based on the volume of gas produced and the market price of natural gas.
- **Technical Effectiveness:** The analysis assumes a technical effectiveness of 21%. As shown in Table 1-4, this considers a recovery efficiency of 75% (reflects the loss of 25% of the gas cannot be used in pipeline injection because the methane concentration is too low to process to pipeline specifications) and destruction efficiency of 75% to account for losses during transport to point of sale and injection into a commercial natural gas pipeline.
- **Technical Lifetime:** 15 years

Degasification for Electricity Generation

Drained methane can be used to fire internal combustion (IC) engines that drive generators to make electricity for sale to the local power grid (USEPA, 2011b). The quality of methane required for use in power generation can be less than that required for pipeline injection. Internal combustion (IC) engine generators can generate electricity using gas that has heat content as low as 300 Btu/cf or about 30% methane. Mines can use electricity generated from recovered methane to meet their own on-site electricity requirements and can also sell electricity generated in excess of on-site needs to utilities (USEPA, 2008b).

Coal mining is a very energy-intensive industry that could realize significant cost savings by generating its own power. Nearly all equipment used in underground mining runs on electricity, including mining machines, conveyor belts, ventilation fans, and elevators. While most of the equipment used in mining operations is used 250 days a year for two shifts per day, ventilation systems are required to run continuously year round. These systems require large amounts of energy, up to 60% of a mine's total electricity usage. Total electricity demand can exceed 24 kWh per ton of coal produced (USEPA, 2008b).

- **Capital Cost:** The cost for this option includes the cost of gas processing to remove gas contaminants (primarily water vapor and solid particles), the electricity generation equipment, and power grid connection equipment. Costs are assumed to be $1,300/kW. Assuming a 2 MW facility and a capacity factor of 90%, total installed capital costs of electricity generation would be $2.7 million. Total installed capital costs for this abatement measure would be $4.5 million, which includes the $850,000 for recovery, assuming 20% owner's costs and 5% contingencies.
- **Annual O&M Costs:** The annual costs include $0.02/kWh for the engine-gen set in addition to the $2.2/Mcf cost of the recovery system. Assuming a 600 Mcf/d flow and 90% capacity total O&M costs would be approximately $0.8 million USD.
- **Annual Benefits:** Revenues in the form of power sales at market electricity prices. A 2 MW capacity generation facility with a 90% capacity factor would be expected to generate

approximately 16,000 MWh of electricity. Assuming an energy price of $0.075/kWh[7], this project would generate $1.2 million in revenue from electricity sales.

- **Technical Effectiveness:** The analysis assumes a technical effectiveness of 28%, assuming a recovery efficiency of 75% and destruction efficiency of 98% in the energy generation unit.
- **Technical Lifetime:** 15 years

II.1.3.3 Degasification for On-site Utilization—Process Heat

This category of abatement measures includes (1) recovery for use in the boiler for supporting in-mine heating and (2) recovery for coal drying.

Mine Boilers

Drained methane can be used to fuel on-site boilers that provide space or water heat to mine facilities. This analysis assumes that existing boilers will be retrofitted to burn methane and that the drained methane is of sufficient quality to fuel the mine's boiler and no additional gas processing is required.

- **Capital Cost:** The costs for this option are primarily associated with the capital cost to retrofit the mine boiler to fire drained gas. The analysis assumes a 8.1 MMBTU/hr[8] average boiler heat load and a retrofit cost of $7,500/MMBTU/hr. Assuming the mine boiler fuel demand was 10 Mcf/hr, total installed capital costs for this abatement measure would be $635,000, which includes $382,000 for the recovery system, $122,000 for boiler retrofit, and an additional 20% in owner's costs and 5% for contingencies.
- **Annual O&M Costs:** The annual costs are the $2.4/Mcf to operate the recovery system. Assuming a 240 Mcf/d flow and 90% capacity, the total O&M costs would be approximately $213,000 USD.
- **Annual Benefits:** Benefits are the energy costs offset by using the drained methane gas as a substitute fuel source (offsetting coal consumption). Revenues associated with this project will be the quantity of coal replaced at the mine mouth coal market price ($/MMBTU).
- **Technical Effectiveness:** The analysis assumes a recovery efficiency of 75% and destruction efficiency of 98% when combusted in mine boiler.
- **Technical Lifetime:** 15 years

Coal Drying

Another on-site direct use application for drained CMM is to use it as a fuel in thermal coal drying operations at coal preparation plants co-located near an underground mine. The existing coal drying process can be retrofitted to burn methane as a supplemental fuel in addition to burning coal. Similar to the mine boiler option, we assumed the CMM will not require further processing to serve as fuel to the dryer.

- **Capital Cost:** The cost of converting the dryer to burn CMM was assumed to be the same as the cost of converting the boiler firing system [$7,500/MMBtu/hr]. The analysis assumed an average coal drying rate of 380 tons/hr (USEPA, 1998). Assuming the average coal dryer heating

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[7] The actual price utilities would be willing to pay will vary depending on market and regulatory environment within the specific country. In the absence of any additional market incentives, purchasers would likely only pay the price of generation in the range of $0.025/kWhr in the United States.

[8] MMBTU/hr = Million British Thermal Units per hour

requirement is 228 MMBTU/hr,[9] CMM gas with a lower heating value of 991 BTU/cf, the total installed capital costs for this abatement measure would be $635,000, which includes $382,000 for the recovery system, $122,000 for boiler retrofit, and an additional 20% in owner's costs and 5% for contingencies.

- **Annual O&M Costs:** The annual costs to operate the recovery system are assumed to be $2.4/Mcf. Assuming a 240 Mcf/d flow and 90% capacity factor, total O&M costs would be approximately $213,000 USD.
- **Annual Benefits:** Benefits are the energy costs offset by using the drained methane gas as a substitute fuel source (offsetting coal consumption). Revenues associated with this project will be the quantity of coal replaced based on assumed energy content (MMBTU/ton) at the mine mouth coal market price ($/MMBTU).
- **Technical Effectiveness:** The analysis uses a technical effectiveness of 28%, which assumes a recovery efficiency of 75% and destruction efficiency of 98% when combusted in mine boiler.
- **Technical Lifetime:** 15 years

II.1.3.4 Combustion through Flaring

After recovering methane using the drainage well technique, mines can choose to flare methane of greater than 30% concentration (USEPA, 2011a). Flare systems considered include an open flare and enclosed combustion system, which consists of a mounted burner where the flame is exposed (open) or the flame is enclosed in a stack. The costs of the flaring system consist of firing equipment and monitoring and metering equipment to validate methane destruction levels.

- **Capital Cost:** The cost of installing a flare system to burn CMM was assumed to be $280/Mcf/day. Assuming an average daily flow rate of 600 Mcf gas, the total installed capital costs for this abatement measure would be $1,239,000, which includes $850,000 for the recovery system, $134,000 for the flare system, and an additional 20% in owner's costs and 5% for contingencies.
- **Annual O&M Costs:** The annual costs to operate the recovery system are assumed to be $2.4/Mcf. Assuming a 600 Mcf/d flow and 90% capacity factor, total O&M costs would be approximately $489,000 USD.
- **Annual Benefits:** There are no revenues associated with this option.
- **Technical Effectiveness:** The analysis uses a technical effectiveness of 28%, which assumes a recovery efficiency of 75% and destruction efficiency of 98% when combusted in flaring system.
- **Technical Lifetime:** 15 years

II.1.3.5 VAM Oxidation

Oxidation technologies (both thermal and catalytic) have the potential to use CH_4 emitted from coal mine ventilation air. Extremely low CH_4 concentration levels (typically below 1%) make it economically infeasible to sell this gas to a pipeline. However, thermal oxidizers can combust the VAM converting it to H_2O and CO_2. VAM oxidation is technically feasible at CH_4 concentrations between 0.25% and 1.25%. For mines with lower VAM concentrations, a supplemental gas is required to bring the concentration above the 0.25% concentration limit.

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[9] MMBTU/hr = Million British Thermal Units per hour

- **Capital Cost:** Abatement measure costs include the ductwork required to collect VAM exhaust from the mine's ventilation system at the surface vents, the design and installation of a thermal oxidizer unit, and any supporting auxiliary equipment. The total installed capital cost of the VAM oxidizer unit is \$23 per unit of recoverable ventilation air flow measured in cubic feet per minute [cfm]. Assuming the recoverable ventilation air flow rate of 100 Mcfm and a CH_4 concentration of 0.2%, capital costs would be \$2.3 million USD (=100,000 cfm X \$23/cfm). The total installed capital costs for this abatement measure would be approximately \$2.8 million after assuming allowances of 20% in owner's costs and 5% for contingencies.
- **Annual O&M Costs:** Annual operating costs include costs to maintain the oxidizer unit, the electricity required to operate the oxidizer blowers (0.075 kWh/mcf), and the periodic relocation costs of moving equipment to the new location of a mine ventilation shaft (every 5 years at a cost of \$4/cfm). Assuming a 100 Mcfm flow rate, total O&M costs would be approximately \$462,000 USD, where VAM blower electricity costs account for 55% of the annual costs, while oxidizer O&M costs represent 28%, and annualized relocation costs make up the balance.
- **Annual Benefits:** Although low-grade heat can be captured from the VAM oxidizer, little economic benefit can be obtained from it and only under special site-specific conditions; for this reason, we assume there are no energy-related benefits for this abatement measure.
- **Technical Effectiveness:** The analysis assumes a technical effectiveness of between 19% and 68%, which assumes a recovery efficiency of 25% (in 2010) to 90% (in 2030) and destruction efficiency of 98% in a VAM oxidation unit.
- **Technical Lifetime:** 15 years

II.1.3.6 Evaluation of Future Mitigation Option and Trends

Based on our review of existing abatement measures, technology improvements have the potential to reduce the costs of VAM oxidation technology. Despite its abatement potential, VAM oxidation is the measure with the highest abatement costs largely due to three key factors that include: (1) the equipment itself is large and costly; (2) the lack of a revenue source; and (3) only a handful of technologies have been demonstrated at a commercial scale and as such economies of scale in production have not been realized. The development of an international carbon market like the United Nations Framework Convention on Climate Change's (UNFCCC's) Clean Development Mechanism (CDM) or the European Trading System (ETS) would provide a source of revenue from the sale of carbon reduction credits. In addition, improvements in design and catalysts have the potential to reduce the cost of oxidation over time. All other abatement measures described in this chapter are assumed to be mature technologies.

II.1.4 Marginal Abatement Costs Analysis

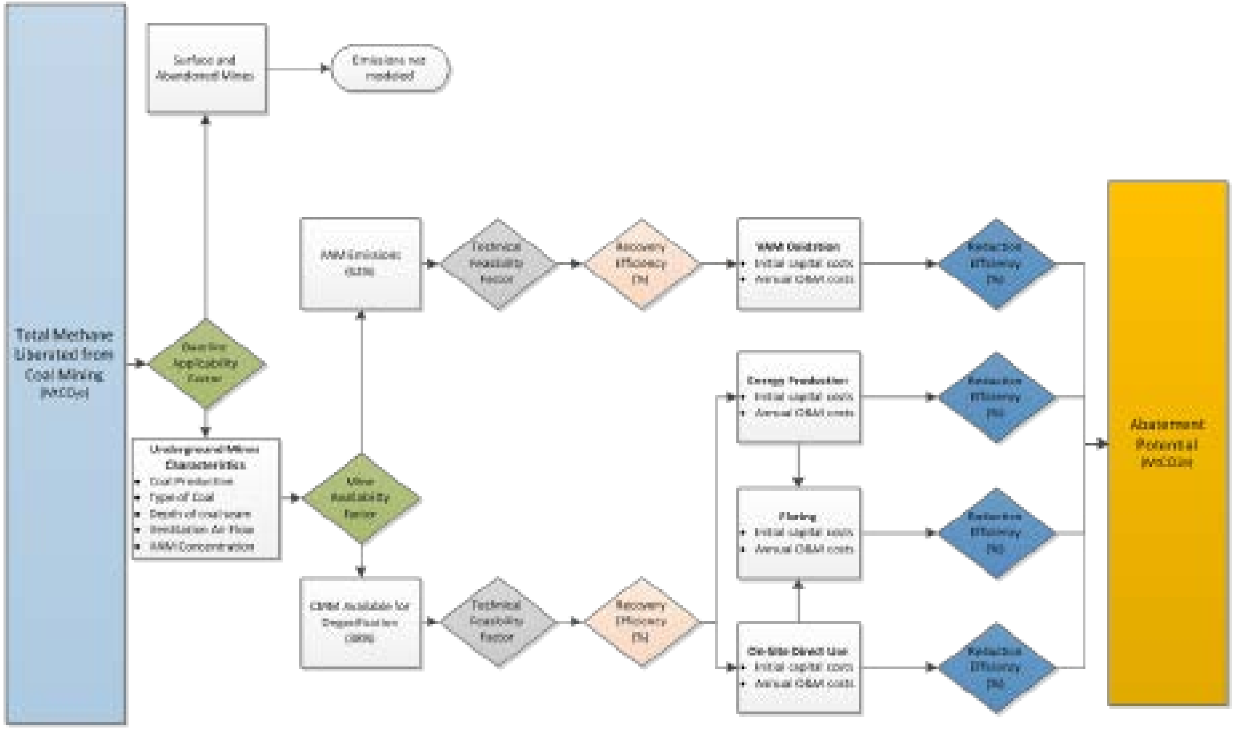
This section describes the methodological approach to the international assessment of CMM abatement measures. Here we describe the modeling approach applied to the sector and highlight the unique facets of the modeling approach that are required to align with the general modeling framework described in the technical summary of this report.

II.1.4.1 Methodological Approach

The analysis seeks to characterize the cost of abatement in the coal mining sector by developing project cost estimates for a series of representative mines that represent the population of active underground coal mines in a reference location, which is the United States. Abatement measures are applied to the technically applicable stream of emissions (degasification, or ventilation air streams). The

MAC model calculates break-even prices for each representative coal mine based on the facility characteristics that include annual methane liberation, presence of existing degasification operations, mine ventilation air flow rate, and VAM concentration. Figure 1-3 illustrates the flow of emissions and the country and technology factors that determine the abatement potential.

Figure 1-3: Flow Chart of the Coal Mining Sector MAC Modeling Approach



The MAC model internationalizes the abatement measures' project costs by applying country-specific factors to adjust individual components of the technology costs and expected benefits (i.e., capital, labor, energy and materials) to transpose costs from a United States context to the international country of interest. The MAC model then applies the general break-even cost calculation using the internationalized costs and benefits to develop country-specific abatement cost estimates.

II.1.4.2 Assessment of Sectoral Trends

Abatement potential estimated in this report is limited to the subset of emissions from underground coal mining activities. No abatement measures are considered for surface mining, abandoned mines, or post-mining operations. The analysis assumed that the majority of emissions from the coal mining sector come from underground coal mining activity. As a result, a significant proportion of the BAU emissions projected (see Table 1-3 above) are available for abatement via the measures discussed in this chapter. This analysis considers country-specific data when available to adjust the basic assumption that between 70% and 98% of emissions are available for abatement (i.e., the quantity of emissions from underground mining activities). For countries for which no other information was available, expert judgment was used to assess the quantity of emissions eligible for abatement.

II.1.4.3 Definition of Model Facilities for the Analysis

A population of representative underground coal mines was developed using publicly available data for the U.S. active underground coal mines. The dataset included detailed information on over 100 active mines with average methane liberation rates greater than 0.1 million cubic feet per day. Information was also available on the methane concentration in mine ventilation air.

The international population of facilities is defined through a representative dataset of underground mines with the accompanying mine-specific characterizations. This includes the gassiness of the mine and the concentration of methane present in the mine's ventilation air.

II.1.4.4 Estimating Abatement Project Costs and Benefits

Mine characteristics for each mine in the facility database were used to estimate abatement project costs and benefits. Applying the costs described in Section II.1.3, the CMOP project Cash Flow Model provided outputs including initial capital investment, annual recurring costs for operation and maintenance, and the quantity of energy saved or offset. The costs and benefits data are then used as inputs in the MAC model. The cost functions used in the CMOP model are assumed to be representative of typical projects in the United States. Please refer to the CMOP model documentation for additional details on how costs are calculated.

Table 1-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits calculated for each coal mine are used in the calculation that solve for the break-even price that sets the project's benefits equal to its costs.

The break-even prices presented in Table 1-5 represent weighted average break-even prices weighted by total annual methane liberated across the population of coal mines used for this analysis. Each coal mine will have its own break-even price based on the amount of methane recovered. Break-even prices will be higher for less gassy coal mines and lower (potentially negative) for most gassy mines. Complete international MAC results are presented in Section II.1.4.5.

Table 1-5: Example Break-Even Price Calculation for Coal Mine Abatement Measures

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs[b] ($/$tCO_2e$)	Net Annual Cost[a] ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break-Even Price[b] ($/$tCO_2e$)
Energy End Uses					
Pipeline Injection	99,629	$18.5	−$19.5	$3.76	−$4.69
Electricity Generation	130,338	$38.7	−$33.0	$7.84	−$2.18
On-Site Direct Use	249,175	$2.5	−$2.8	$0.50	−$0.85
Excess Gas Flaring					
Enclosed Flare System	298,333	$1.7	$5.0	$0.35	$6.33
Combustion of VAM					
VAM Oxidation	46,430	$37.5	$28.0	$7.61	$57.91

[a] Assumes tax rate = 40%; discount rate = 10%, technical lifetime = 15 years

[b] AEO 2010 Energy prices; dry natural gas ($/Mcf); electricity $/kWh); and coal ($/ton)

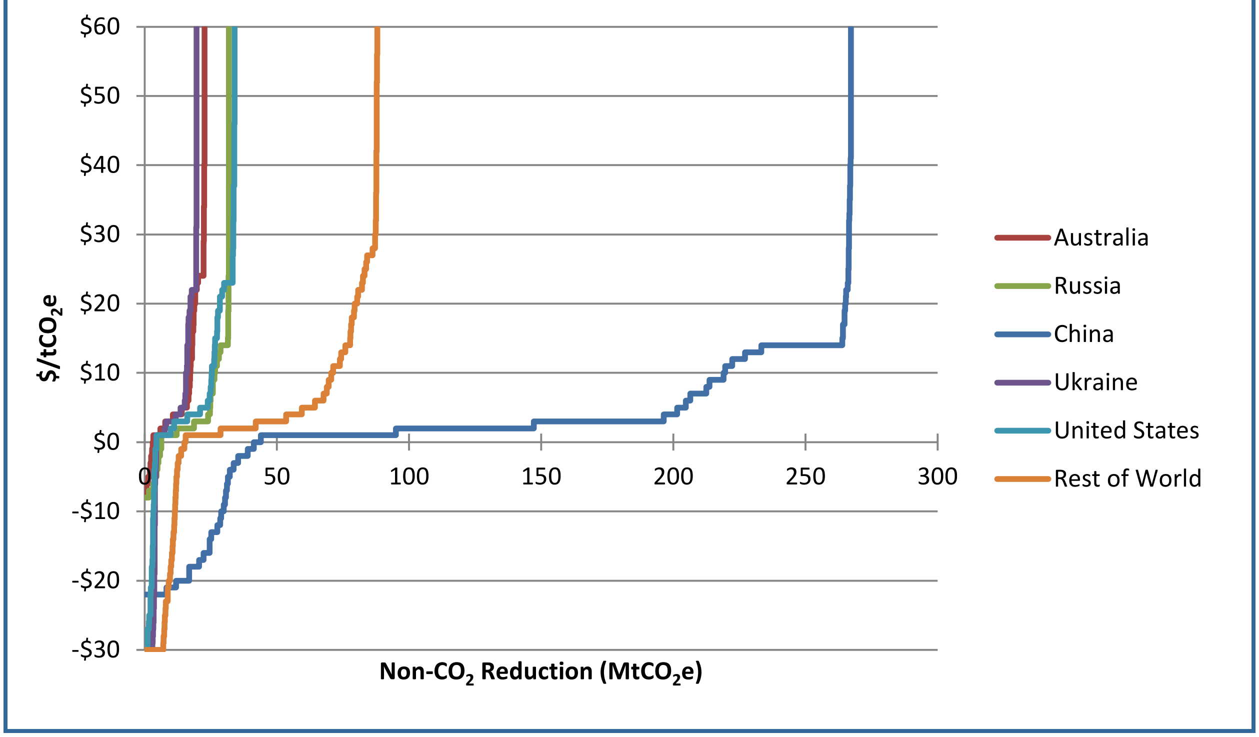
II.1.4.5 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 400 and 468 $MtCO_2e$, respectively. Nearly 16% of the reduction can be achieved by implementing currently available technologies that are cost-effective at projected energy prices. If an additional emission reduction incentive (e.g., tax incentive, subsidy, or tradable emission reduction credit) above the zero break-even price were available to coal mine operators, then additional emission reductions could be cost-effectively achieved. The results of the MAC analysis are presented in Table 1-6 and Figure 1-4 by major country and regional grouping at select break-even prices in 2030.

Table 1-6: Abatement Potential by Region at Selected Break-Even Prices ($/$tCO_2e$) in 2030

	Break-Even Price ($/$tCO_2e$)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Australia		1.9	3.3	15.9	17.3	18.0	19.1	22.4	22.6	22.7	22.9
China	29.8	32.2	43.9	204.7	219.6	264.2	265.3	266.5	267.2	269.6	269.6
Russia		4.5	6.3	24.8	26.6	31.5	31.6	31.8	31.8	32.1	32.1
Ukraine	3.8	4.2	4.4	15.1	16.0	16.4	17.3	19.5	19.6	19.6	19.7
United States	3.4	3.6	4.5	23.8	25.4	27.4	28.5	33.5	34.0	34.2	34.5
Rest of Region											
Africa	1.0	1.0	1.1	6.0	6.6	7.5	7.5	7.5	7.6	7.7	7.7
Central and South America	1.6	1.6	1.9	6.7	7.8	8.0	8.3	9.8	9.9	9.9	10.0
Middle East	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Europe	2.1	2.4	2.6	10.8	11.9	12.4	13.0	15.1	15.2	15.2	15.4
Eurasia	0.0	0.0	1.3	8.5	9.6	11.0	11.0	11.1	11.1	11.2	11.2
Asia	6.5	6.8	8.2	30.9	34.0	37.4	38.9	41.9	42.1	42.3	42.4
North America	0.2	0.2	0.3	1.3	1.4	1.4	1.5	1.7	1.8	1.8	1.8
World Total	**48.5**	**58.6**	**77.7**	**348.7**	**376.2**	**435.3**	**442.2**	**461.1**	**463.0**	**466.4**	**467.6**

Figure 1-4: Marginal Abatement Cost Curve for Top 5 Emitters and Rest of World in 2030



II.1.4.6 Uncertainties and Limitations

Several key limitations in current data availability constrain the accuracy of this analysis. Successfully addressing these issues would improve development of the MACs and predictions of their behavior as a function of time. Some of these limitations include the following.

- **Accurate Distribution of Mine Type for Each Country.** Extrapolating from available information about individual mines to project fugitive emissions at a national level implies that the available data are representative of the country's coal production not already included in the existing database. A more accurate distribution of representative mines would improve the accuracy of the cost estimates and the shape of each MAC. These data would include mines of all sizes, emissions factors, and production levels. This lack of information becomes increasingly problematic when evaluating a country such as China, where the majority of mines are small and private mines are not represented in currently available data sources.
- **Country-Specific Tax and Discount Rates.** In this analysis, a single tax rate was applied to mines in all countries to calculate the annual benefits of each technology. Similarly, the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately quantify benefits and break-even prices.
- **Improved Information on Public Infrastructure.** A more detailed understanding of each country's natural gas infrastructure would improve the estimates of costs associated with transporting CH_4 from a coal mine to the pipeline. Countries with little infrastructure will have a much higher transportation cost associated with degasification and enhanced degasification technologies.

- **Concentrations for VAM in International Mines.** The effectiveness and applicability of VAM technology depends on VAM concentration and mine-specific coal production rates. Improved data on the VAM concentration levels for individual mines would enhance the accuracy of cost estimates. This information would also help to more accurately identify the minimum threshold concentration levels that make VAM oxidation an economically viable option.

References

Global Methane Initiative (GMI). 2010. *Coal Mine Methane Country Profiles*. This document provides individual profiles for 37 countries that covers coal production and coal mine methane markets. Available at: http://www.globalmethane.org/tools-resources/coal_overview.aspx.

Mine Safety and Health Administration (MSHA). January 7, 2010. 2008 Mine Data. Personal communications with Chad Hancher at MSHA. Coal Mine Data, methmine08nma.xls.

Somers, J. M and L. Schultz. 2009."Coal Mine Methane Ventilation Air Methane: New Mitigation Technologies." Available at: http://www.epa.gov/cmop/resources/vam.html.

U.S. Energy Information Administration (USEIA). 2011. *International Energy Outlook 2011*. Coal Overview. DOE/EIA-0484(2011). Washington, DC: EIA. Available at: www.eia.gov/forecasts/ieo/.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). 2011a. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. Annex 3 Methodological Descriptions for Additional Source or Sink Categories.* USEPA #430-R-11-005. Washington, DC: USEPA. Obtained on May 5, 2011, at: http://epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). 2011b. *User's Manual for Coal Mine Methane Project Cash Flow Model (Version 2).* Obtained January 25, 2010, at: http://www.epa.gov/cmop/docs/cashflow_user_guide.pdf.

U.S. Environmental Protection Agency (USEPA). *Coal Mine Methane Project Cash Flow Model (Version 2)*. Obtained on January 25, 2010, at: http://www.epa.gov/cmop/resources/index.html.

U.S. Environmental Protection Agency (USEPA). July 2008a. *U.S. Surface Coal Mine Methane Recovery Project Opportunities*. USEPA #430-R-08-001. U.S. EPA Coalbed Methane Outreach Program. Obtained on January 7, 2011, at: http://www.epa.gov/cmop/docs/cmm_recovery_opps_surface.pdf.

U.S. Environmental Protection Agency (USEPA). September 2008b. (Revised January 2009). *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Profiles of Selected Gassy Underground Coal Mines 2002-2006*. EPA 430-K-04-003. U.S. EPA Coalbed Methane Outreach Program. Obtained January 7, 2010, at http://www.epa.gov/cmop/docs/profiles_2008_final.pdf.

U.S. Environmental Protection Agency (USEPA). 2004. *Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Profiles of Selected Gassy Underground Coal Mines 1999–2003*. EPA 430-K-04-003. Washington, DC: Office of Air and Radiation. Available at: http://www.epa.gov/cmop/docs/profiles_2003_final.pdf.

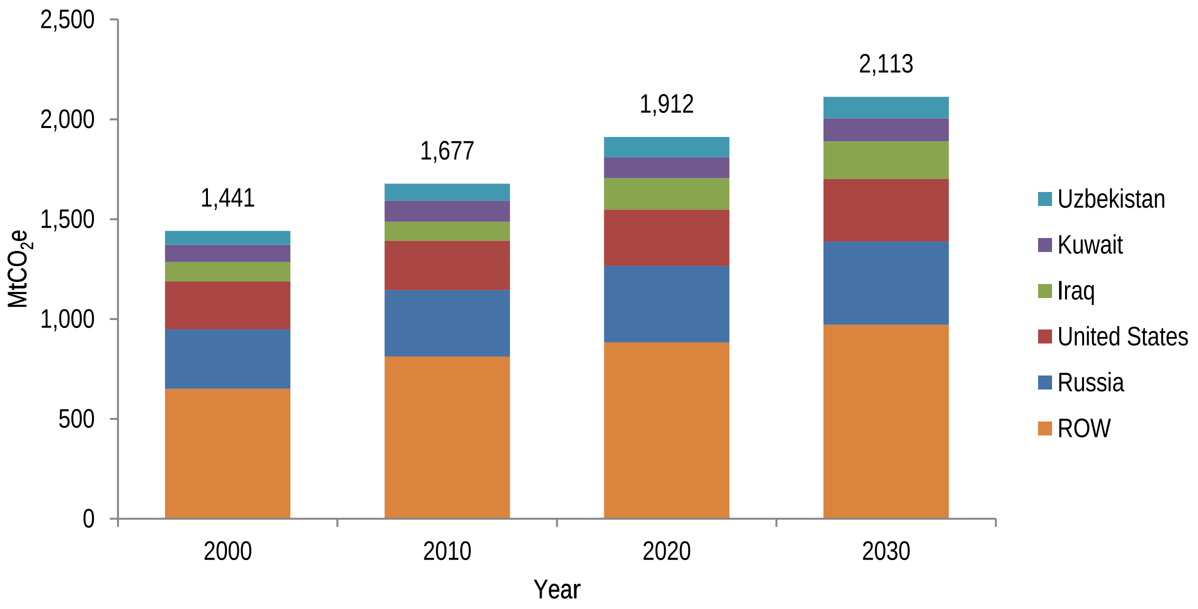
U.S. Environmental Protection Agency (USEPA). November 1998. Use of Coal Mine Methane in Coal Dryers. (US)EPA Coalbed Methane Outreach Program Technical Options Series. USEPA #6202J. Washington, DC: USEPA. Obtained on January 7, 2011, at: http://www.epa.gov/cmop/docs/016red.pdf.

II.2. Oil and Natural Gas Systems

II.2.1 Sector Summary

Oil and natural gas (ONG) systems are a leading source of anthropogenic CH_4 emissions, emitting 1,677 $MtCO_2e$ or 23% of total global CH_4 emissions in 2010 (USEPA, 2012a). Russia, the United States, Iraq, Kuwait, and Uzbekistan accounted for more than half of the world's CH_4 emissions in this sector in 2010. Figure 2-1 presents the business-as-usual baseline projections for the ONG sector between 2000 and 2030.

Figure 2-1: Emissions Projections for the Oil and Natural Gas Systems Sector: 2000–2030

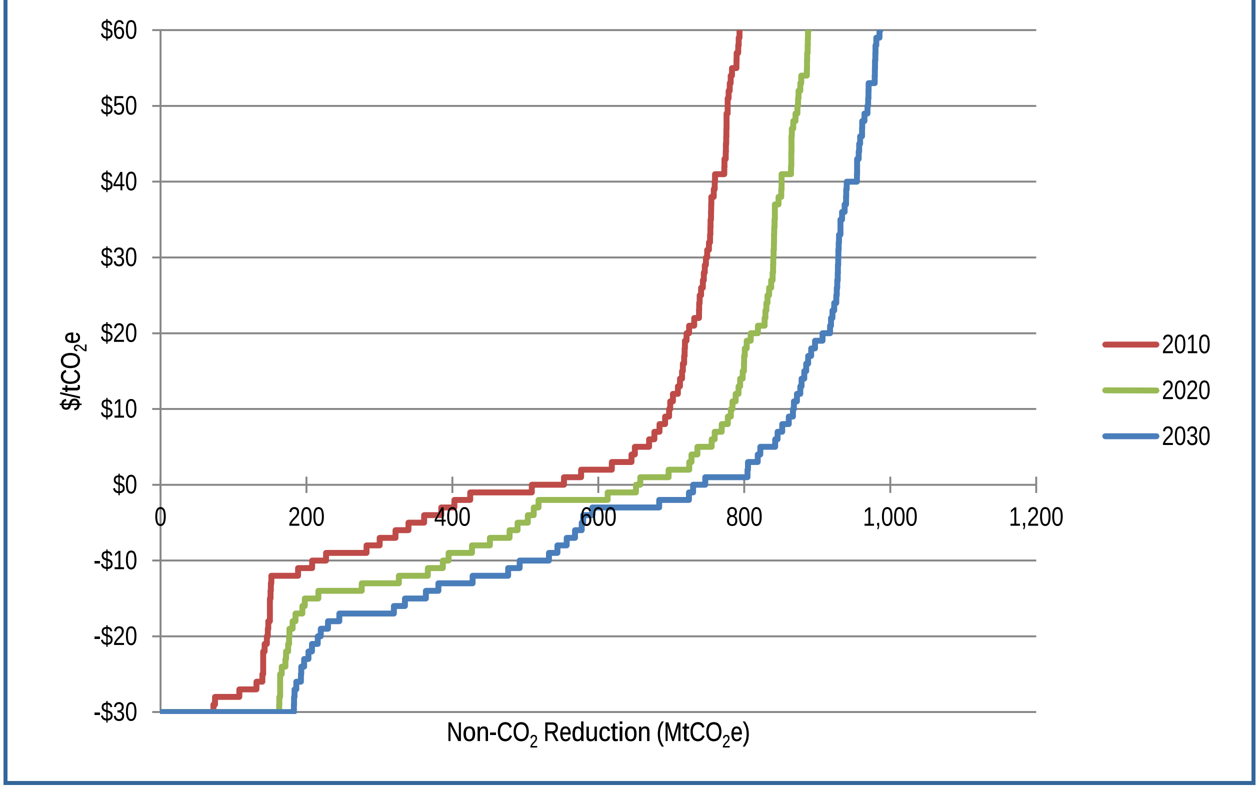


Source: U.S. Environmental Protection Agency (USEPA), 2012a

ONG system emissions are projected to grow 26% between 2010 and 2030 with Brazil and Iraq experiencing the highest rate of growth at 128% and 100%, respectively, over the same time period.

A number of abatement measures are available to mitigate CH_4 losses from activities associated with or directly from the operation of equipment components common across the ONG system segments of production, processing, transmission, and distribution. These abatement options in the ONG system segments generally fall into three categories: equipment modifications/upgrades; changes in operational practices, including direct inspection and maintenance (DI&M); and installation of new equipment. The abatement measures may be applied to components and equipment used in ONG operations, including compressors/engines, dehydrators, pneumatics/controls, pipelines, storage tanks, wells, and other processes and equipment commonly used in some or all of the ONG system segments. The global abatement potential associated with the suite of abatement measures applicable for ONG systems is illustrated in the marginal abatement cost (MAC) curves for 2010, 2020, and 2030 presented in Figure 2-2.

Figure 2-2: Global Abatement Potential in Oil and Natural Gas Systems: 2010, 2020, and 2030



Note: Figure 2-2 does not show the entire MAC curve, an additional 10% of abatement potential is available at prices > $60/tCO2e.

Global abatement potential in the ONG sector is 60% of the sector emissions in 2010, or 997 $MtCO_2e$. The abatement potential increases over time, growing to 1,103 and 1,218 $MtCO_2e$ in 2020 and 2030 respectively (representing 58% of each years' BAU emissions). Nearly 70% of the abatement potential is achievable at a carbon prices below $5. In addition, over 61% of abatement (747 $MtCO_2e$ in 2030) is cost-effective at current energy prices (i.e. a carbon price ≤ $0/$tCO_2e$).

The following section briefly explains CH_4 emissions from ONG systems. This is followed by international CH_4 emissions projections. Subsequent sections characterize the abatement technologies and present the costs and potential benefits. Finally, this chapter concludes with a discussion of the MAC analysis and the regional results.

II.2.2 Methane Emissions: Oil and Natural Gas Systems

CH_4 is the principal component of natural gas.[1] Fugitive CH_4 is emitted through activities and components associated with the natural gas production, processing, transmission, and distribution. Oil production and processing upstream of oil refineries can also emit CH_4 in significant quantities through

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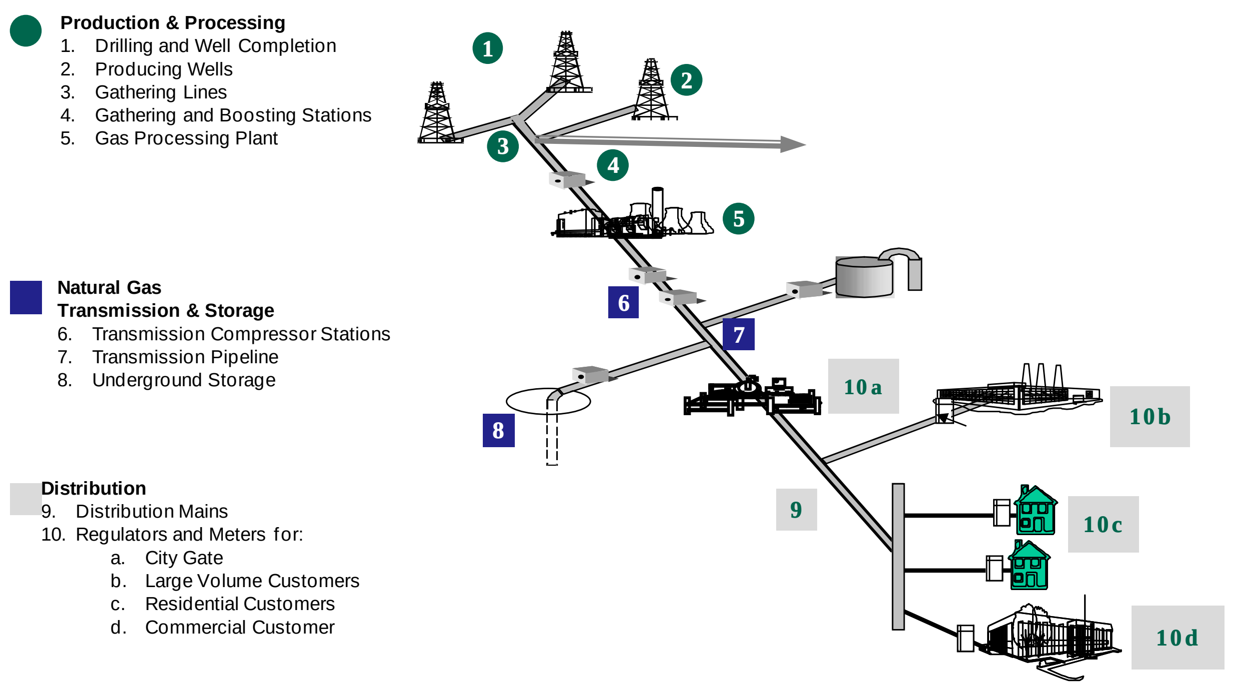
[1] CH_4 concentrations typically increase as the natural gas moves from production to distribution. Typically CH_4 concentrations in non-associated gas are assumed to be 80% at production, increasing to 87% in processing, and 95% in transmission and distribution. Associated gas typically has a lower concentration (between 65 and 75%) depending on the presence of other hydrocarbons in the gas mix.

routine venting, flaring, and other fugitive sources associated with the production, transmission, upgrading, and refining of crude oil and distribution of crude oil products (IPCC, 2006). Figure 2-3 identifies the facilities and equipment associated with the ONG system segments.

Figure 2-3: Segments of Oil and Natural Gas Systems



Source: Adapted from American Gas Association (AGA) and Natural Gas STAR Program.

Table 2-1 provides examples of the typical facilities and equipment that comprise ONG systems. Fugitive CH_4 emissions result from equipment leaks, system upsets, process venting, and deliberate flaring at oil and gas production fields, natural gas processing facilities, natural gas transmission lines and compressor stations, natural gas storage facilities, and natural gas distribution lines (USEPA, 2012a).

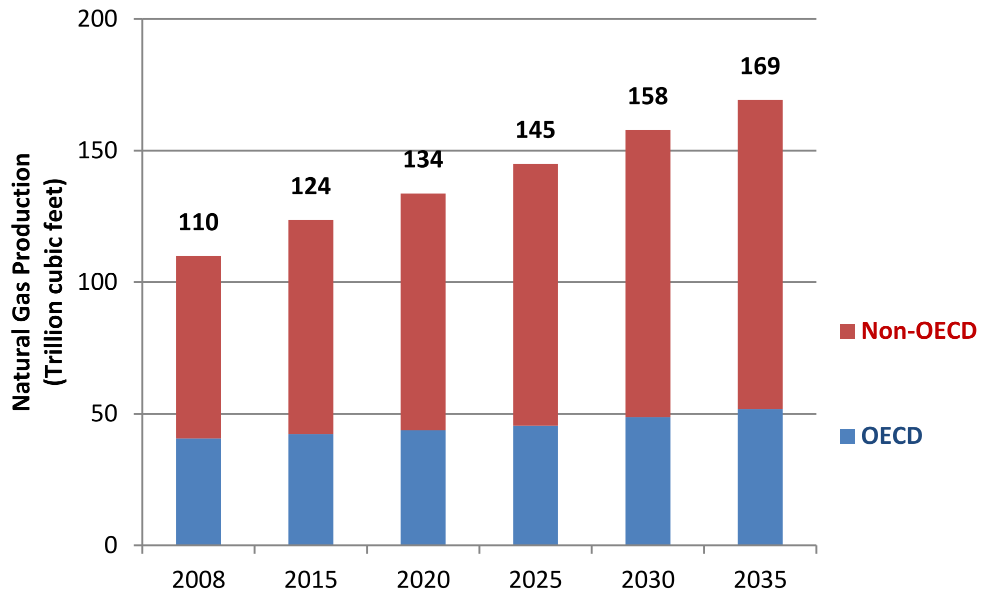
Table 2-1: Emissions Source from Oil and Natural Gas Systems

Segment	Facility	Equipment at the Facility
Production	Wells, central gathering facilities	Separators, pneumatic devices, chemical injection pumps, dehydrators, compressors, heaters, meters, pipelines, liquid storage tanks
Processing	Gas plants	Vessels, dehydrators, compressors, acid gas removal (AGR) units, heaters, pneumatic devices
Transmission and storage	Transmission pipeline networks, compressor stations, meter and pressure-regulating stations, underground injection/withdrawal facilities, liquefied natural gas (LNG) facilities	Vessels, compressors, pipelines, meters/pressure regulators, pneumatic devices, dehydrators, heaters
Distribution	Main and service pipeline networks, meter and pressure-regulating stations	Pipelines, meters, pressure regulators, pneumatic devices, customer meters

II.2.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

Emissions from ONG systems are closely correlated with the quantity of ONG produced and consumed. Globally, production and consumption of natural gas are expected to increase in both the near term and long term. Between 2008 and 2035, natural gas supplies are expected to increase by almost 60 trillion cubic feet, or roughly 1.6% per year (EIA [U.S. Energy Information Administration], 2011a). The majority of production growth is projected to occur in non-Organisation for Economic Co-operation and Development (OECD) countries most notably, in the Middle East, Asia, and Africa regions, where production growth rates average 2.8, 2.5, and 2.4% per year, respectively. Figure 2-4 presents projected global gas production by major region from 2008 to 2035. Growth in natural gas production from non-OECD countries between 2015 and 2035 is projected to be twice the growth in production from OECD countries. Expanded production in non-OECD countries is expected to exceed regional demand allowing for net exports to OECD countries.

Figure 2-4: Global Natural Gas Production: 2015–2035



Source: U.S. Energy Information Administration (EIA). (2011a). *International Energy Outlook 2011*. Table G1. World total natural gas production by region, Reference case, 2008–2035.

Another trend in the international gas market is the increased production of unconventional gas resources (i.e., tight gas, shale gas, and coalbed methane). Preliminary international estimates suggest that the quantity of "technically recoverable shale gas resources" is equal to all existing proven natural gas reserves worldwide (EIA, 2011b). Although the unconventional gas resources have not been fully assessed, energy experts are projecting significant increases in production over 2035 time horizon. The most notable increases are expected in the United States, Canada, and China, where unconventional gas is expected to account for 47, 51, and 72% of domestic production, respectively, in 2035 (EIA, 2011a). Technology advancements in horizontal drilling and hydraulic fracturing have enabled the United States to tap into its vast unconventional gas resources. Emerging research on extraction techniques from shale gas formations suggests there are different emissions profiles compared with conventional gas production.

II.2.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emission trends globally and presents the baseline emissions used in the MAC analysis.[2]

Historical Emissions Estimates

Emissions from ONG systems globally grew by 31% between 1990 and 2010 with an average annual growth rate of 1.4%. Key factors that contributed to the growth in emissions include expansions in ONG production and increases in natural gas consumption.

Projected Emissions Estimates

Worldwide CH_4 emissions from ONG systems are projected to increase by 26% between 2010 and 2030 (an average annual rate of 1.2%), slightly lower than in early years (1990–2010). By 2030, the top 5 emitting countries are projected to account for 55% of global emissions in this sector. Although Russia and the United States remain the largest emitters in this sector, their relative share of the world's emissions is expected to fall slightly as the ONG industry in Africa and the Middle East expands in future years. Table 2-2 presents the projected baseline CH_4 emissions for the top 5 emitting countries and remaining country groups by world region.

Table 2-2: Projected Baseline CH_4 Emissions for Oil and Natural Gas Systems by Country/Region: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
Russia	332.0	341.9	382.8	401.8	417.9	1.2%
United States	247.8	258.3	281.6	307.2	313.1	1.2%
Iraq	94.1	109.2	157.8	172.9	187.9	3.5%
Kuwait	106.0	106.9	103.8	108.2	115.9	0.4%
Uzbekistan	84.7	95.8	102.7	104.9	107.3	1.2%
Rest of Regions						
Africa	274.5	292.2	291.1	302.9	315.1	0.7%
Central and South America	58.0	59.7	67.7	75.8	84.2	1.9%
Middle East	131.5	138.6	131.4	136.1	137.9	0.2%
Europe	42.8	41.6	40.9	41.3	42.4	0.0%
Eurasia	90.8	104.8	112.0	115.7	120.4	1.4%
Asia	128.4	141.1	149.7	156.7	164.8	1.3%
North America	86.6	88.2	90.2	97.2	106.1	1.0%
World Total	1,677.3	1,778.3	1,911.8	2,020.6	2,112.9	1.2%

[a]CAGR = Compound Annual Growth Rate

Source: USEPA, 2012a.

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[2] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's Global Emissions Projection Report available at: http://www.epa.gov/climatechange/economics/international.html. Note that national emissions inventories are often recalculated when new data become available. The Inventory of U.S. Emissions and Sinks (the source of United States emissions estimate presented in this report) has been updated since this analysis was conducted, and the revised 2010 value for oil and gas methane emissions is 174 $MtCO_2e$.

II.2.3 Abatement Measures and Engineering Cost Analysis

Within the four segments of ONG systems, a number of abatement measures can be applied to mitigate CH_4 losses from activities associated with or directly from the operation of equipment and components. The abatement measures, such as inspection and maintenance programs for leaks or equipment retrofits or modifications, may be applied to ONG processes and equipment, including compressors/engines, dehydrators, pneumatics/controls, pipelines, storage tanks, and wells.

Abatement measures available to mitigate CH_4 losses from activities associated with or directly from the operation of equipment components common across the ONG system segments of production, processing, transmission, and distribution. These abatement options in the ONG system segments generally fall into three categories: equipment modifications/upgrades; changes in operational and maintenance practices including DI&M; and installation of new equipment. ONG industry-related voluntary programs such as the Global Methane Initiative (GMI) and USEPA's Natural Gas STAR Program, which are aimed at identifying cost-effective CH_4 emission reduction opportunities, have developed a well-documented catalog of potential CH_4 abatement measures that are applicable across the segments of the ONG system. Abatement measures documented by the USEPA's Natural Gas STAR Program serve as the basis for estimating the costs of abatement measures used in this analysis. It is important to note that although abatement measures identified by the Natural Gas STAR Program are cited as cost-effective based on Industry Partner-reported experiences, the abatement measure's cost-effectiveness is determined by the component's emissions rate and the value of energy recovered. This analysis uses average emission factors when estimating the break-even prices for each measure. In many cases, these average emission rates are lower than the case study examples cited in the Natural Gas STAR Program's documentation. As a result, abatement measures cited as cost-effective by the Natural Gas STAR Program's Partners may not necessarily be the lowest cost options in the MAC analysis.

This section discusses the abatement measures considered for this analysis and presents the costs, benefits, technical applicability, reductions efficiency, and the expected technology lifetime of each measure. The abatement measures presented in Tables 2.3 through 2.6 provide an overview of the options considered in each segment of the oil and gas sector. A more complete list of the abatement measures included in the Oil and Gas Sector MAC model is provided as Appendix D to this chapter.

II.2.3.1 Oil and Natural Gas Production

The production segment of the ONG system consists of wells, compressors, dehydrators, pneumatic devices, chemical injection pumps, heaters, meters, pipeline, liquid storage tanks, and central gathering/storage facilities. Table 2-3 presents the list of abatement measures applied to the production segment of ONG systems. In addition, this section characterizes two important abatement measures considered in the production segment: reduced emissions from hydraulically fractured gas well completions and installation of vapor recovery units (VRUs) on crude oil storage tanks.

Reduced Emissions for Hydraulically Fractured Natural Gas Well Completions

Reduced emissions completion (REC) is a method designed to capture 90% of the gas that would otherwise be flared or vented during new well construction and workovers on existing wells that are hydraulically fractured. Equipment includes a sand trap, separator, and a gathering line to route gas to sales pipelines or reserve tanks. Depending on the well field operations and frequency of well completions, it may be more cost-effective to rent rather than purchase capital equipment (USEPA, 2011a). The use of RECs will result in increased sales of recovered gas. Furthermore, condensate may also

Table 2-3: Abatement Measures Applied in Oil and Gas Production Segments

Abatement Measure	Component	Total Installed Capital Cost ($2008)	Annual O&M ($2008)	Time Horizon	Technical Effectiveness[a]
Directed Inspection & Maintenance at Gas Production Facilities	Chemical Injection Pumps	—	6,675	1	40%
Installing Surge Vessels for Capturing Blowdown Vents	Compressor BD	158,940	28,078	15	50%
Installing Electronic Starters on Production Field Compressors	Compressor Starts	2,649	5,849	10	75%
Directed Inspection & Maintenance at Gas Production Facilities	Deepwater Gas Platforms	—	50,000	1	95%
Install Flash Tank Separators on dehydrators	Dehydrator Vents	6,540	—	5	30% to 60%
Optimize glycol circulation rates in dehydrators	Dehydrator Vents	—	15	1	33% to 67%
Installing Catalytic Converters on Gas Fueled Engines and Turbines	Gas Engines - Exhaust Vented	7,924	4,374	10	56%
Installing Plunger Lift Systems in Gas Wells	Gas Well Workovers	5,646	(13,855)	5	80%
Replace Gas-Assisted Glycol Pumps with Electric Pumps	Kimray Pumps	2,788	1,949	10	100%
Directed Inspection & Maintenance at Gas Production Facilities	Non-associated Gas Wells	—	817	1	95%
Installing Plunger Lift Systems in Gas Wells	Non-associated Gas Wells	5,646	(13,855)	5	80%
Directed Inspection & Maintenance on Offshore Oil Platforms	Offshore Platforms, Deepwater oil, fugitive, vented and combusted	—	50,000	1	43%
Flaring Instead of Venting on Offshore Oil Platforms	Offshore Platforms, Shallow water Oil, fugitive, vented and combusted	165,888,859	4,976,666	15	98%
Installing Vapor Recovery Units on Storage Tanks	Oil Tanks	473,783	161,507	15	58%
Using Pipeline Pump-Down Techniques to Lower Gas Line Pressure Before Maintenance	Pipeline BD	—	1,352	1	90%
Directed Inspection & Maintenance at Gas Production Facilities	Pipeline Leaks	—	82	1	60%
Convert Gas Pneumatic Controls to Instrument Air	Pneumatic Device Vents	72,311	24,321	10	50% to 90%
Replacing High-bleed Pneumatic Devices in the Natural Gas Industry	Pneumatic Device Vents	165	—	10	8% to 17%

(continued)

Table 2-3: Abatement Measures Applied in Oil and Gas Production Segments (continued)

Abatement Measure	Component	Total Installed Capital Cost ($2008)	Annual O&M ($2008)	Time Horizon	Technical Effectiveness[a]
Directed Inspection & Maintenance at Gas Production Facilities	Shallow water Gas Platforms	—	33,333	1	95%
Reduced Emission Completions for Hydraulically Fractured Natural Gas Wells	Unconventional Gas Well Completions	—	30,038	1	90%
Reduced Emission Completions for Hydraulically Fractured Natural Gas Wells	Unconventional Gas Well Workovers	—	30,039	1	90%
Installing Surge Vessels for Capturing Blowdown Vents	Vessel BD	158,940	28,078	15	50%
Installing Plunger Lift Systems in Gas Wells	Well Clean Ups (LP Gas Wells)	5,646	(13,855)	5	40%

[a] Technical effectiveness reflects the percentage reduction achievable from implementing the abatement measure considering the presence of complementary options. Technical effectiveness is the product of three separate factors—the reduction efficiency, technical applicability, and market penetration.

[b] Lower technical effectiveness is due to limited applicability at LP gas wells.

be sold, generating additional revenue. The actual savings generated from these sales also depends on the market price of gas and gas liquids. Although hydraulically fractured natural gas well completions are currently limited to the United States and Canada, the analysis assumes that this technology will be adopted by other countries over time.

- **Capital cost:** This analysis assumes that natural gas producers rent the REC equipment from a third-party service provider hence there are no initial capital costs. If a well operator were to be purchase equipment, the capital cost of the equipment would be approximately $500,000 or more depending on the complexity of the REC set-up (USEPA, 2011a).
- **Annual operation and maintenance (O&M) cost:** Cost of implementing this abatement measure represents the incremental cost of REC to recover the gas over the traditional well completion cost. The equipment rental costs range between $700 and $6,500/per day (equivalent to $815 to $7,568 in 2008 dollars). Completions typically take between 3 and 10 days. This analysis assumes 7 days for well clean-up and completions at a cost of $30,000 in 2008 dollars.
- **Annual benefits:** Revenues may be derived from gas sales from avoided venting/flaring operations. Additional benefits could come from the sale of recovered natural gas condensate. In the United States, an average of 34 barrels of condensate are recovered during each completion or recompletion (USEPA, 2011b). Although the value of the recovered gas condensate would be determined by the gas composition, based on an assumed price of $70 per barrel (bbl), the recovered gas condensate would contribute an additional $2,400 in revenues per completion or recompletion.
- **Applicability:** This technique applies to hydraulically fractured gas well completions and workovers.
- **Technical Effectiveness:** This analysis assumes a technical effectiveness is 54% which is the product of the 90% reduction efficiency and a technical applicability of 60% and market penetration of 100%.

- **Technical lifetime**: 1 implementation event per year per hydraulically fractured well.

Install Vapor Recovery Units (VRUs)

Crude oil and condensate storage tanks are widely used to stabilize the flow of oil or condensate between wells and transportation sites. Inside these tanks, light hydrocarbons (often with a heavy concentration of methane) dissolved in the crude oil or condensate flash out of solution and collect between the liquid and the roof of the tank. As liquid levels fluctuate, vapors are often vented into the atmosphere. VRUs can capture 95% of these light hydrocarbon vapor emissions (USEPA, 2006a). The recovered vapors can be sold or used on site as fuel.

- **Capital costs:** Capital costs range from $40,000 to $120,000 (equivalent to $50,000 to $140,000 in 2008 dollars), depending on the capacity of the unit (between 25 and 500 Mcf per day), sales line pressure, number of tanks, size and type of compressor, and the degree of automation. Installation costs range from 50 to 100% of the capital equipment cost and vary depending on the location of the tanks and the size of the VRU required.
- **Annual costs**: Incremental annual O&M costs are about 15% of initial cost. The annual costs are determined by the capacity of the VRU, as well as the location (weather), electricity costs, and the type of oil produced.
- **Annual benefits**: VRUs can reduce the hydrocarbon vapor emissions of hydrocarbon liquid storage tanks by about 95%. The vapors that are recovered can be used in several different ways. They can be used on site as fuel (where their value is equal to the price of the fuel they displaced). Alternatively, the vapors can be piped to a natural gas gathering pipeline or to a processing plant that separates the natural gas liquids and the methane and sells them separately. Because the recovered vapors generally have a higher Btu content than pipeline quality natural gas, the vapors are more valuable and sell for a higher price on an energy content basis.
- **Applicability**: Applied to crude oil and condensate storage tanks
- **Technical Effectiveness:** The technical effectiveness of this option is 58% based on a reduction efficiency of 95%, technical applicability of 61%, and a market penetration of 100%.
- **Technical Lifetime**: 15 years

For detailed discussion of other options available to the ONG production segments, we refer the reader to USEPA's Natural Gas STAR Program website.

II.2.3.2 Gas Processing and Transmission Segments

The processing segment of the natural gas system consists of gas plant facilities that incorporate the use of vessels, dehydrators, compressors, acid gas removal (AGR) units, heaters, and pneumatic devices. The transmission segment consists of transmission pipeline networks, compressor stations, and meter and pressure-regulating stations. Table 2-4 and Table 2-5 present the list of abatement measures applied to the gas processing and gas transmissions segment of a natural gas system. Similar to the previous section, this section briefly characterizes four important abatement measures considered in the gas processing and transmission segment.

Directed Inspection & Maintenance (DI&M) on Processing Plants and Booster Stations

DI&M is a cost-effective approach to reduce methane emissions from leaking components throughout the oil and natural gas industry including at natural gas processing plants. The activities include a four-part process that identifies, prioritizes, and implements the most cost-effective emissions reductions. Step 1 of the process is to identify and measure the leaks using leak detection and measurement techniques.

Table 2-4: Abatement Measures for the Natural Gas Processing Segment

Abatement Measure	Component	Total Installed Capital Cost ($2008)	Annual O&M ($2008)	Time Horizon	Technical Effectiveness[a]
Installing Surge Vessels for Capturing Blowdown Vents	Blowdowns/Venting	158,940	28,078	15	50%
Directed Inspection & Maintenance at Processing Plants and Booster Stations - Compressors	Centrifugal Compressors (dry seals)	—	15,581	1	12%
Directed Inspection & Maintenance at Processing Plants and Booster Stations - Compressors	Centrifugal Compressors (wet seals)	—	6,131	1	12%
Replacing Wet Seals with Dry Seals in Centrifugal Compressors	Centrifugal Compressors (wet seals)	380,804	(102,803)	5	66%
Installing Catalytic Converters on Gas Fueled Engines and Turbines	Gas Engines - Exhaust Vented	7,924	4,374	10	56%
Replace Gas-Assisted Glycol Pumps with Electric Pumps	Kimray Pumps	2,788	1,949	10	100%
Directed Inspection & Maintenance at Processing Plants and Booster Stations	Plants	—	10,134	5	95%
Directed Inspection & Maintenance at Processing Plants and Booster Stations - Compressors	Recip. Compressors	—	6,131	1	10%
Early replacement of Reciprocating Compressor Rod Packing Rings	Recip. Compressors	7,800	0	5	1%
Fuel Gas Retrofit for BD valve - Take Recip. Compressors Offline	Recip. Compressors	2,365	—	5	21%
Reciprocating Compressor Rod Packing (Static-Pac)	Recip. Compressors	5,696	—	5	0%

[a] Technical effectiveness reflects the percentage reduction achievable from implementing the abatement measure considering the presence of complementary options. Technical effectiveness is the product of three separate factors: the reduction efficiency, technical applicability, and market penetration.

Steps 2 and 3 are to assess the measurements to determine which leaks are most cost-effective to repair by comparing the value of the natural gas lost through leakage to the overall cost of repair. Lastly, in Step 4 a survey plan is developed for future DI&M to focus efforts on those sources most likely to be leaking and reduce the cost of subsequent programs. Although the initial expense of the survey can be relatively high, it was found that the costs can be recovered in the first year through reductions in gas leakage. USEPA (2003a) documentation suggests the initial baseline survey cost is typically between $1 and $2 per component on average. Depending on their size, typical processing facilities may have between 14,000 and 55,000 components. Subsequent follow-up surveys are found to cost significantly less compared with the initial survey, because they are more targeted to the components that are most likely to leak and the most beneficial to repair.

Table 2-5: Abatement Measures for the Natural Gas Transmission Segment

Abatement Measure	Component	Total Installed Capital Cost ($2008)	Annual O&M ($2008)	Time Horizon	Technical Effectiveness[a]
Directed Inspection and Maintenance at Compressor Stations - Compressors	Centrifugal Compressors (dry seals)	—	15,581	1	13% to 14%
Replacing Wet Seals with Dry Seals in Centrifugal Compressors	Centrifugal Compressors (wet seals)	380,804	(102,803)	5	71% to 77%
Install Flash Tank Separators on dehydrators	Dehydrator Vents	9,504	—	5	67%
Optimize glycol circulation rates in dehydrators	Dehydrator vents	—	15	1	67%
Installing Catalytic Converters on Gas Fueled Engines and Turbines	Engine/Turbine Exhaust Vented	7,924	4,374	10	56%
Directed Inspection and Maintenance at Gate Stations and Surface Facilities	M&R (Trans. Co. Interconnect)	—	1,741	1	72%
Directed Inspection and Maintenance on Transmission Pipelines	Pipeline Leaks	—	41	1	60%
Using Pipeline Pump-Down Techniques to Lower Gas Line Pressure Before Maintenance	Pipeline venting	—	1,352	1	90%
Convert Gas Pneumatic Controls to Instrument Air	Pneumatic Devices	72,311	24,321	10	50% to 90%
Replacing High-bleed Pneumatic Devices in the Natural Gas Industry	Pneumatic Devices	165	—	10	8% to 17%
Directed Inspection and Maintenance at Compressor Stations - Compressors	Recip Compressor	—	15,581	1	10% to 12%
Early replacement of Reciprocating Compressor Rod Packing Rings	Recip Compressor	7,800	—	5	1%
Early replacement of Reciprocating Compressor Rod Packing Rings and Rods	Recip Compressor	41,068	—	5	1% to 74%
Fuel Gas Retrofit for BD valve - Take Recip. Compressors Offline	Recip Compressor	2,365	—	5	36% to 39%
Reciprocating Compressor Rod Packing (Static-Pac)	Recip Compressor	5,696	—	5	6% to 9%
Installing Surge Vessels for Capturing Blowdown Vents	Station venting	158,940	28,078	15	50%
Directed Inspection and Maintenance at Compressor Stations	Stations	—	1,398	1	85%
Directed Inspection and Maintenance at Gas Storage Wells	Wells (Storage)	—	651	1	95%

[a] Technical effectiveness reflects the percentage reduction achievable from implementing the abatement measure considering the presence of complementary options. Technical effectiveness is the product of three separate factors: the reduction efficiency, technical applicability, and market penetration.

DI&M analysis parameters include:

- **Capital costs:** There is no capital costs associated with this option.
- **Annual costs:** Initial survey design and leak detection, measurement, and repair. This analysis assumes a $1 to $2 cost per component for leak detection and repair. The analysis assumes an average processing plant has approximately 14,000 components.
- **Benefits:** Gas savings from emission reductions.
- **Applicability**: Applicable to gas processing, gas gathering and booster stations, gas storage wells, gate stations and surface facilities, and transmission compressor stations.
- **Technical Effectiveness**: This analysis assumes a technical effectiveness of 95% based on a 95% reduction efficiency, a 100% technical applicability factor, and a 100% market penetration factor.
- **Technical Lifetime**: This analysis assumes a 1 year technical lifetime.

Identify and Replace or Retrofit High-Bleed Pneumatic Devices

Pneumatic devices are widely used as controllers and monitors in the production sector, pressure regulators and valve controllers in the processing sector, and actuators and regulators in the transmission sector of the natural gas industry. When driven by natural gas, pneumatic devices release or bleed natural gas into the atmosphere and thus are a leading source of methane emissions in the natural gas industry. Replacing high-bleed devices with low-bleed devices and installing low-bleed retrofit kits on operating devices can reduce emissions by between 50 and 90% (USEPA, 2006b).

- **Capital costs:** Capital costs are the main component of replacement and retrofitting and vary greatly among the options. Multiple options can be employed at once to reduce gas bleed. Some typical options include replacing high-bleed level and pressure controllers with low-bleed controllers, reducing supply pressure, and repairing leaks. This analysis assumes the capital cost to be $165, which represents the incremental cost between a high bleed device and a low bleed device (USEPA, 2011b).
- **Annual costs:** Some improved maintenance costs are recurring. Maintenance costs are small relative to the cost of equipment. Replacing and retrofitting devices can potentially reduce annual maintenance costs. For this analysis the incremental operation and maintenance (O&M) cost is assumed to be $0.
- **Benefits:** Revenue from gas savings of reduced methane leakage. Reductions in methane emissions range from 45 to 260 Mcf per device annually depending on the device and application.
- **Applicability**: Applicable for high to moderate bleed pneumatic devices in the gas transmission segments.
- **Technical Effectiveness:** Technical effectiveness for this option ranges between 8% and 16% depending on the gas bleed rate. This analysis assumes a reduction efficiency of 9% (low bleed), 23% (medium bleed) and 25% (high bleed). The technical applicability of 50%, 75%, and 90% for low-, medium-, and high-bleed devices, respectively. Market penetration rate is assumed to be 100% for all devices.
- **Technical Lifetime**: 10 years

Reducing Methane Emissions from Compressor Rod Packing Systems

In natural gas compressors, the packing systems are used to maintain a tight seal around the piston rod, preventing unwanted gas leakage while allowing the rod to move freely (USEPA, 2006). Leak rates depend on the fit, alignment of the packing parts, and wear. New packing systems installed on smooth, well-aligned compressor rods can be expected to leak as little as 11.5 scfh. Leak rates increase as the system ages because of wear on the packing rings and piston rod. Regularly monitoring and replacing these systems can result in cost savings and emissions reductions. This abatement measure is applied to compressors in the gas processing and transmission segments of the natural gas system. Packing systems comprise flexible rings that are secured around the compressor shaft. Packing cups hold the rings in place, and a nose gasket reduces leaks around the packing cups. Conventional packing rings have a life expectancy of about 3 to 5 years, but when the packing breaks down, leaks tend to increase so dramatically that it may be desirable to replace packing rings even more frequently. A new, well-functioning system could leak as little as 11 standard cubic feet per hour (scfh), compared with worn compressor rod packing systems that have leak rates as high as 900 scfh (USEPA, 2006c).

- **Capital costs:** Replacement compressor rod packing systems range from $7,800 per unit to replace the packing rings to over $41,000 for replacement of the piston rods and packing rings.
- **Annual costs:** There are no annual costs for these options.
- **Benefits:** Revenue from gas savings of reduced methane leakage.
- **Applicability**: Applies to reciprocating compressors located at processing plants and compressor stations in the transmission segment
- **Technical Effectiveness:** Technical effectiveness for this option is 1.5%, based on a reduction efficiency of 10% a technical applicability of 15%, and a market penetration of 100%.
- **Technical Lifetime**: 5 years.

Replacing Wet Seals with Dry Seals in Centrifugal Compressors

Centrifugal compressors are used in the production, processing, and transmission of natural gas. The seals located on the rotating shafts to reduce methane leakage have traditionally been "wet" (oil) seals. Replacement of wet seals with dry seals leads to substantially reduced emissions and operating costs. The dry seals are the only piece of capital equipment required and may be installed during a scheduled downtime. The lifetime of dry seals may be double that of wet seals, and they also emit significantly lower emissions. It has been estimated that the wet seals may pay for themselves in as little as 11 months (USEPA, 2006d). Other benefits include lower electricity requirements and maintenance costs and increased operating efficiency of the compressor and pipeline, which may also lead to higher gas sales.

- **Capital costs:** This analysis assumes a capital cost of $381,000 in 2008 dollars for wet seal replacement on a compressor with a shaft beam size of 6 inches. Cost of dry seals ($15,200 per shaft inch) represents 48% of initial capital costs; equipment testing services (~0.5% of equipment cost); engineering, procurement, and construction (EPC) services were assumed to be 100% of equipment and testing costs.
- **Annual costs:** O&M costs of dry seals are expected to be less than O&M costs for wet seals because of reduced electricity requirements, increased operating efficiency of the compressor, increased reliability of the compressor, and potentially lower maintenance costs. Hence, incremental recurring costs are assumed to equal a cost savings of just over $100,000 each year. These incremental cost savings are added to the annual benefits resulting from increased gas sales.
- **Benefits:** Revenue from gas savings of reduced methane leakage. Other annual cost savings due to lower operation and maintenance costs are captured in the annual costs.
- **Applicability**: Applies to centrifugal compressors located at gas processing plants and compressor stations in the transmission segment.

- **Technical Effectiveness:** Technical effectiveness for this option is 66%. This value is based on a reduction efficiency of 85%, a technical applicability of 78% and a market potential of 100%.
- **Technical Lifetime**: 5 years

II.2.3.3 Gas Distribution Segment

The distribution segment consists of main and service pipeline networks, meter and pressure-regulating stations, pneumatic devices, and customer meters. Table 2-6 presents the list of abatement measures applied to the distribution segment of a natural gas system. DI&M activities' cost and benefit components are discussed below.

Table 2-6: Abatement Measures for the Distribution Segment

Abatement Measure	Component	Total Installed Capital Cost ($2008)	Annual O&M ($2008)	Time Horizon	Technical Effectiveness[a]
Directed Inspection and Maintenance at Gate Stations and Surface Facilities	M&R <100	—	1,604	1	30% to 80%
Replace Cast Iron Pipeline	Mains—Cast Iron	373,633	182	5	95%
Replace Unprotected Steel Pipeline	Mains—Unprotected steel	373,633	182	5	95%
Replace Unprotected Steel Service Lines	Services—Unprotected steel	418,023	311	5	95%

[a] Technical effectiveness reflects the percentage reduction achievable from implementing the abatement measure considering the presence of complementary options. Technical effectiveness is the product of three separate factors: the reduction efficiency, technical applicability, and market penetration.

DI&M at Gate Stations and Surface Facilities

Leaking meters, pipes, valves, flanges, fittings, open-ended lines, and pneumatic controllers at gate stations and surface facilities are a significant source of methane emissions. DI&M is a proven and cost-effective way to detect, measure, prioritize, and repair equipment leaks to reduce methane emissions and achieve gas savings (USEPA, 2003b). To implement DI&M, first, a baseline survey identifies and quantifies leaks at gate stations and surface facilities. The results of this survey are then used to direct repairs toward the components that were identified as being most susceptible to leaking and the most profitable to repair. Then, the results of the initial survey are used to guide subsequent inspections and maintenance.

- **Capital costs:** There are no capital costs associated with this option.
- **Annual costs:** The costs associated with starting a DI&M program are the cost of labor and equipment for identifying leaking components and estimating the mass leak rate of those components; the labor cost for recording survey information; the labor cost of pinpointing leaking components that are cost-effective to repair; the cost of parts, labor, and equipment downtime to fix the leaks; and the cost of labor for developing a plan that directs future inspection and maintenance. Costs differ depending on the type of screening and measurement equipment used and the characteristics of the staff who conduct the surveys and repairs. Maintenance and repair are ongoing, so most costs are recurring. Annual costs vary depending on the frequency and comprehensiveness of the surveys and repairs. Over time, the scope and frequency of the surveys can be fine-tuned, as patterns emerge. This analysis assumes an average annual cost of $1,600 in 2008 dollars.

- **Benefits:** Gas savings and methane emissions reductions vary widely depending on the number of stations involved in the DI&M program and how long the program has been operating.
- **Applicability**: Applies to components inside gate stations and surface facilities.
- **Technical Effectiveness** 30% to 80%; higher efficiency for facilities handling higher volumes of natural gas. Technical effectiveness measure assumes reduction efficiency between 30% and 80%, technical applicability of 90% to 100% and a market penetration of 100%.
- **Technical Lifetime**: 5 years

II.2.4 Marginal Abatement Costs Analysis

This section discusses the methodological approach used to conduct the international MAC analysis in the ONG sector.

II.2.4.1 Methodological Approach

The MAC analysis approach consists of four sequential steps. Step 1 was to assess the sectoral trends, which entailed reviewing recent international energy statistics for oil and gas. The second step was to develop source-level emission estimates that could be used to build different model ONG systems. These model systems reflect country-specific variations in production process techniques, level of maintenance, and vintage of the existing infrastructure. Step 3 was to estimate country-specific abatement costs and benefits based on the relative cost factors for labor, energy, and non-energy inputs. Step three was to compute the break-even prices for each country-specific abatement measure. Finally, the MAC model computes the abatement potential as a cumulative reduction for each measure assuming full (system-wide) implementation. Sorting the break-even prices lowest to highest, the incremental reductions are cumulated to construct the MAC curve presented in Section II.2.4.2.

Assessment of Sectoral Trends

The objective in assessing the sectoral trends is to understand how emissions differ across countries and how they vary over time. This not only considers aggregate growth or decline in emissions but also any potential shift in sector emissions across the oil and gas segments. To this end, we reviewed the current international gas and oil industry activity data for 2010. Statistics reviewed included gross natural gas production, oil production, LNG imports, and gas processing throughput (EIA, 2011; *Oil & Gas Journal*, 2011). In the absence of real infrastructure data, these statistics provide insights on the relative importance of segments internationally. Table 2-7 presents these key statistics for the 10 largest emitting countries in 2010.

Table 2-7: International Statistics on Key Activity Drivers: 2010

Country	2010 Emissions ($MtCO_2e$)	Dry Natural Gas Production[a] (Bcf/year)	Crude Oil Production[b] (Mbbl/day)	Gas Processing Plant Throughput[c] (MMcfd)	Gas Transmission Pipelines[d] (km)
Russia	332.0	22,965	10,146	926	160,952
United States	247.8	26,858	9,688	45,808	548,665
Kuwait	106.0	422	2,450	1,034	269
Iraq	94.1	596	2,408	1,550	3,365
Angola	84.9	364	1,988	137	-
Uzbekistan	84.7	2,123	105	NA	10,253
Libya	77.4	1,069	1,789	2,567	-
Canada	53.3	6,695	3,483	29,154	75,835
Iran	47.2	7,774	4,252	10,509	20,725
Venezuela	30.2	2,510	2,375	3,555	5,347

[a] EIA. International Energy Statistics: Gross Natural Gas Production.

[b] EIA. International Energy Statistics: Total Oil Supply.

[c] *Oil & Gas Journal* [*OGJ*]. June 6, 2011. *Worldwide Processing Survey*.

[d] CIA. 2011. The World Factbook.

[e] EIA. 2012. Country analysis Brief–Uzbekistan. Available at: http://www.eia.gov/countries/cab.cfm?fips=UZ

Although differences in annual production and throughput provide some indication of the size of a country's ONG system, considerations of age and the condition of the infrastructure are major factors in determining the rate of source-level emissions and in turn the abatement potential associated with each abatement measure. In general, countries with aging infrastructure will have "leakier" components and in turn have a greater abatement potential. Conversely, countries with newly developed infrastructure will have less abatement potential.

Another important trend to consider is the expansion of unconventional gas (shale gas) production. The growth in unconventional gas production (e.g., the United States, Canada, and China) is likely to result in an increased frequency of hydraulically fractured gas well completions and related workovers. In the absence of any regulatory or voluntary actions to reduce emissions from these sources, this trend suggests that the gas production segment will represent an even greater proportion of these nations' baseline emissions over time.

Defining International Model Facilities for the Analysis

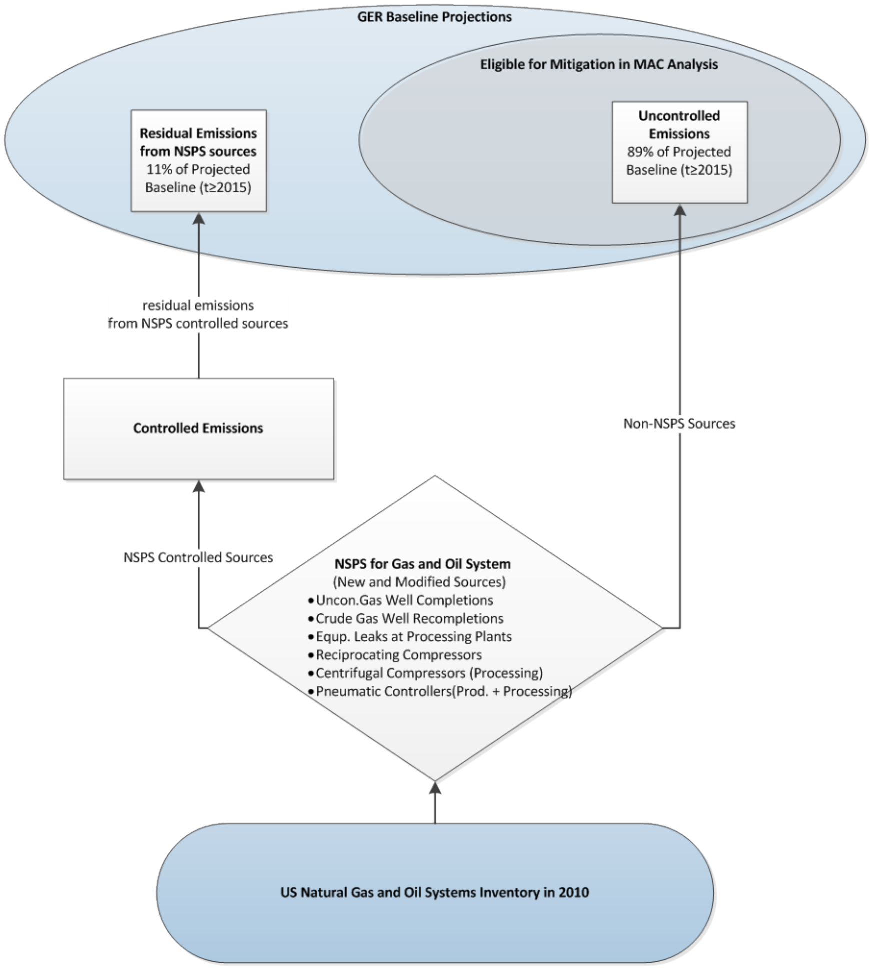
For this analysis, we developed model ONG systems for each segment based initially on the USEPA ONG system emissions inventory. Scaling factors were developed based on country-specific activity factors developed from the international statistics illustrated in Table 2-6. Where reliable data were available, international adjustments were made to reflect specific country systems. For countries for which data were not available, this analysis assumed the gas and oil system was similar to that in the United States in terms of the distribution of emissions (total BAU emissions for each country is exogenous to the MAC model obtained from USEPA, 2012a). The relative international factor was multiplied by the percentage share of U.S. gas and oil CH_4 emissions inventory at the segment/component source level (e.g., compressors, valves, connections, pneumatic devices). The resulting "Technical Applicability" (TA) factor is used to allocate a fraction of the national baseline emissions to each component source in the ONG inventory (e.g., wells, tanks, compressors, valves).

Multiplying the TA factor by the baseline emissions yields the subset of emissions available for reductions from each component source and abatement measure. The TA factor comprises two parts. The U.S. 2010 GHG emissions inventory serves as the basis for the distribution of emissions across the constituent components (see USEPA, 2012b, Annex 3). The second component of the TA factor is the country- and segment-specific relative activity factor (e.g., total oil production, gross natural gas production).

Regulatory Considerations for the U.S. Natural Gas and Oil System

Special considerations were made for the United States to reflect the New Source Performance Standards (NSPS) regulation that was in effect starting in year 2012. This regulation will affect the production and processing segments of the ONG system by requiring the use of abatement measures included in this analysis to control for volatile organic compound (VOC) emissions from major new and modified emitting sources in the United States. This mitigation is no longer considered additional and thus should be removed from the U.S. domestic MAC curve. For the purposes of this analysis, we have removed emissions sources covered under the NSPS regulation and any subsequent abatement potential that would have come from these sources. Figure 2-5 illustrates the key elements that led us to the resulting distribution of emissions.

Figure 2-5: Diagram of BAU Emissions for the United States Oil and Natural Gas System



To capture the impact of the NSPS regulation for model years 2015 and beyond, we needed to estimate the relative distribution of emissions that will be associated with controlled and uncontrolled sources. We start with the 2010 U.S. inventory (USEPA, 2012), which is the basis of our analysis. Next, we identify all components in the inventory subject to the NSPS in the production and processing segments.

For the NSPS controlled sources, we applied controls to these components using the reduction efficiency (%) for each abatement measure from the MAC model to estimate the level of abatement achieved by the NSPS rule. In Figure 2-5, controlled emissions equals the sum of reductions achieved across the NSPS sources. The residual emissions from NSPS sources are assumed to be included in the projected baselines (2015 to 2030).

For the purposes of this analysis, we estimated residual emissions from controlled sources were 11% of projected emissions, while emissions from uncontrolled sources were 89% of projected emissions. We applied these shares to the baseline projections for years ≥ 2015.

This approach assumes a fixed distribution of emission over time in the MAC model. We recognize the limitations of this assumption and would ideally like to apply a trend to the shares for model years beyond 2015. Unfortunately, at the time of writing this report, data to develop this trend were not available. Any future work related to the U.S. MAC curve should consider developing a more dynamic trend that more accurately estimates the level of NSPS-controlled emissions and the subsequent distribution of emissions in the baseline projections over time.

Based on the analysis described here, the United States' abatement potential presented in the MAC modeling results can be summarized in the following expression:

$$Abatement\ Potential(USA) = \sum Uncontrolled\ Emissions_{i,t} * Technical\ Effectiveness_{i,j,t}$$

where:

$Technical\ Effectiveness_{i,j,t} = Reduction\ Efficiency_{i,j,t} * Tech\ Applicability_{i,j,t} * Market\ Penetration_{i,j,t}$

i = Uncontrolled emissions source

j = Abatement technology

t = Modeled year

Estimate Abatement Project Costs and Benefits

Turning to the abatement measures discussed in Section II.2.3, the analysis begins with technology costs for the United States as reported in the USEPA Lesson Learned documentation. We applied the Nelson-Farrar[3] Oil Field and Refinery Operation cost indices to convert from reported-year costs to 2008 dollars (USD) for capital and O&M costs, respectively. Next, we applied the country-specific relative price factors for labor, energy, and nonenergy components of annual costs and benefits. This final step yielded country-specific costs and benefits used to compute the break-even price for each abatement measure. Abatement measure costs and technical efficiencies were applied to estimate the break-even prices. Table 2-7 presents the break-even prices for selected ONG system abatement measures for the United States in 2010. For this analysis, we used the abatement measure costs, revenue, and reduction efficiency as described in Section II.2.3 to estimate the break-even price for each abatement measure. A complete list of ONG system abatement measures is presented in Appendix C.

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[3] Nelson-Farrar Annual Cost Indices are available in the first issue of each quarter of the *Oil and Gas Journal*.

The first step is to estimate the reduced emissions on a per unit basis for each technology. This value is calculated by multiplying the abatement measure's technical efficiency by the annual emissions per unit of the component or process to which the abatement measure is being applied. The resulting annual reduced emissions serve as the denominator in the break-even price calculation.

In Table 2-8 we present abatement cost and revenues per metric ton of CO_2 equivalent (tCO_2e) reduced for the abatement measures with the largest national emissions reductions. Costs include the annualized total installed capital cost and annual O&M costs. Offsetting these costs are the annual revenue in terms of gas savings and the tax benefit of depreciation. The break-even prices reported in Table 2-8 are calculated by subtracting the annual revenues from the annualized costs.

Table 2-8: Example Break-Even Price Calculation based on 2010 MAC for the United States

Abatement Measure	System Component/ Process	Reduced Emissions per Unit (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Annual Cost ($\$/tCO_2e$)	Annual Revenue ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break-Even Price ($\$/tCO_2e$)	National Incremental Reductions ($MtCO_2e$)
Production								
Convert Gas Pneumatic Controls to Instrument Air	Pneumatic Device Vents	71.0	$335.68	$441.41	$10.01	$82.50	$684.58	15.29
Reduced Emission Completions for Hydraulically Fractured Natural Gas Wells	Unconventional Gas Well Completions	2,703.96	$0.00	$11.11	$10.01	$0.00	$1.10	8.82
Replacing High-bleed Pneumatic Devices in the Natural Gas Industry	Pneumatic Device Vents	9.7	$7.38	$0.00	$10.01	$1.81	−$4.44	2.30
Processing								
Directed Inspection & Maintenance at Processing Plants and Booster Stations	Plants	1,109.0	$0.00	$9.14	$10.01	$0.00	−$0.87	0.50
Fuel Gas Retrofit for BD valve - Take Recip. Compressors Offline	Recip. Compressors	351.9	$2.96	$0.00	$10.01	$0.90	−$7.95	1.34
Replacing Wet Seals with Dry Seals in Centrifugal Compressors	Centrifugal Compressors (wet seals)	5,000.8	$33.48	−$20.56	$10.01	$10.15	−$7.24	2.53
Transmission								
Convert Gas Pneumatic Controls to Instrument Air	Pneumatic Devices	89.9	$2,898.32	$3,811.28	$10.01	$712.36	$5,987.24	2.88
Directed Inspection and Maintenance at Compressor Stations	Stations	3,655.9	$0.00	$0.41	$10.01	$0.00	−$9.60	6.61
Fuel Gas Retrofit for BD valve - Take Recip. Compressors Offline	Recip Compressor	1,014.8	$1.07	$0.00	$10.01	$0.32	−$9.26	5.65
Distribution								
Directed Inspection and Maintenance at Gate Stations and Surface Facilities	M&R >300	511.6	$0.00	$3.40	$10.01	$0.00	−$6.60	1.58
Directed Inspection and Maintenance at Gate Stations and Surface Facilities	M&R 100-300	220.2	$0.00	$7.90	$10.01	$0.00	−$2.10	2.48
Replace Cast Iron Pipeline	Mains—Cast Iron	91.7	$1,790.73	$1.99	$10.01	$543.06	$1,239.65	2.54

Note: Break-even price assumes a 10% discount rate and a 40% tax rate. Annual energy benefits are based on a natural gas price of $4/Mcf

From Table 2-8, the annualized capital cost are calculated using the total installed capital costs discussed in Section II.2.3 and expressed in the following equation:

$$Annualized\ Costs = \frac{Total\ Capital\ Cost}{ER \cdot (1 - TR) \cdot \sum_{t=1}^{T} \frac{1}{(1 + DR)^t}}$$

Where:

ER = Annual reduced emissions per unit (e.g. compressor, well, dehydrator, etc.)

TR = Tax rate

T = Technology lifetime in years

DR = Discount rate

Annual O&M costs and expected revenues are calculated using the following equations. International variation in break-even prices is achieved by using regionally adjusted prices for energy labor and materials when computing the country specific annual costs and benefits.

$$Annual\ O\&M\ Costs = \frac{Annual\ O\&M\ Costs}{ER}$$

$$Annual\ Revenues = \frac{Annual\ Revenues}{ER}$$

The tax benefit of depreciation is calculated for each option using the following equation:

$$Tax\ Benefit\ of\ Depreciation = \frac{Total\ Capital\ Costs}{ER \cdot T} \cdot \frac{TR}{(1 - TR)}$$

Finally, the break-even price is calculated by subtracting the benefits from the costs as shown in the equation below.

$$\begin{aligned} &Break\text{-}even\ Price \\ &\quad = Annualized\ Capital\ Cost + Annual\ O\&M\ Cost - Annual\ Revenues \\ &\quad - Tax\ Benefit\ of\ Depreciation \end{aligned}$$

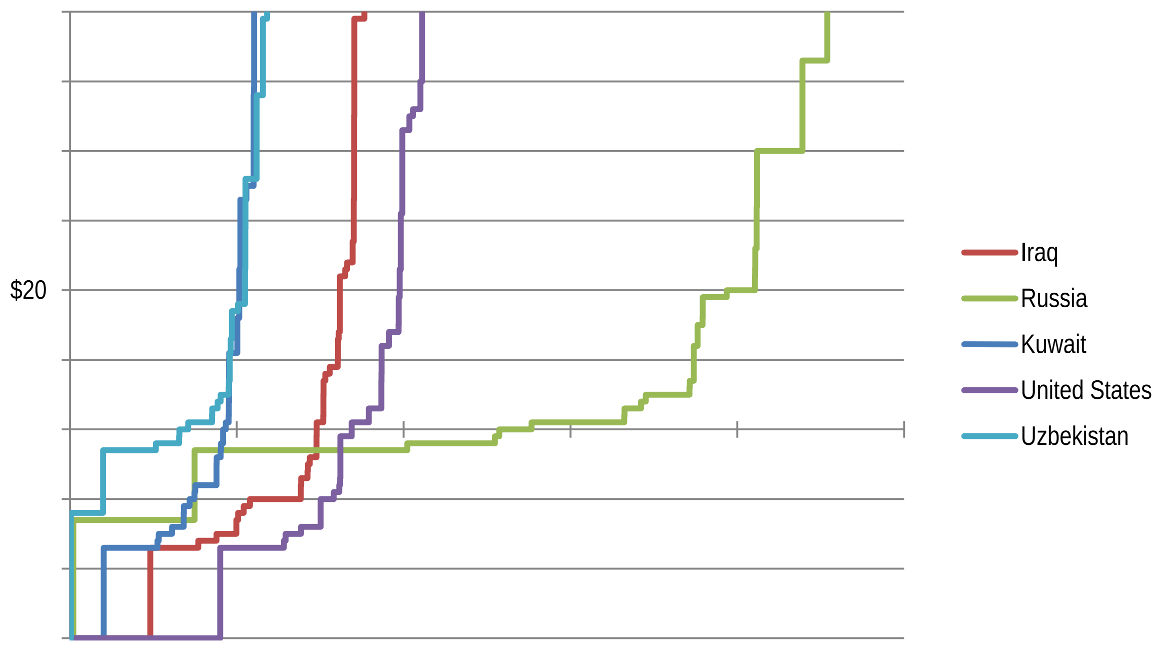
II.2.4.2 MAC Analysis Results

As highlighted at the beginning of this chapter, global abatement potential related to ONG systems equates to approximately 58% of total annual emissions. MAC curve results are presented in Table 2-9 and Figure 2-6. Maximum abatement potential for ONG systems is 1,218 $MtCO_2e$ in 2030. For the year 2030, the results suggest that 842 $MtCO_2e$ or 40% of CH_4 reductions in the ONG sector can be achieved at carbon prices less than or equal to $5/$tCO_2e$. Furthermore over 35% of the 2030 emission reductions (747 $MtCO_2e$) are cost-effective at current energy prices (carbon prices ≤ $0/$tCO_2e$). However, because natural gas prices vary greatly by region, the break-even price and quantity of cost effective reductions varies by country.

Table 2-9: Abatement Potential by Region at Selected Break-Even Prices in 2030

	Break-Even Price ($/tCO$_2$e)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Iraq	69.2	71.9	73.9	76.0	80.3	80.9	80.9	85.1	85.2	89.9	110.0
Kuwait	37.3	44.0	46.7	47.6	47.7	50.1	50.7	51.1	55.2	58.6	73.5
Russia	37.3	37.3	138.3	185.7	187.0	189.6	205.3	205.8	219.5	232.8	266.9
United States	79.1	81.0	84.4	93.3	93.4	98.5	98.8	99.2	105.5	109.7	140.5
Uzbekistan	9.9	9.9	35.4	47.6	47.9	48.5	52.4	52.6	57.8	59.6	68.3
Rest of Region											
Africa	116.3	124.0	124.1	129.4	135.8	136.2	141.4	142.2	145.0	149.3	178.8
Central and South America	31.8	32.7	32.8	34.2	36.2	36.3	37.4	38.3	38.4	40.6	49.4
Middle East	43.2	51.6	53.3	55.3	57.8	58.5	58.7	60.7	61.2	63.6	78.4
Europe	15.0	16.0	16.3	16.8	17.2	17.4	18.0	18.2	18.8	19.8	26.1
Eurasia	22.9	23.3	42.6	51.0	52.3	53.5	56.9	57.0	61.6	64.2	76.7
Asia	40.4	55.8	59.2	62.7	69.4	71.0	72.1	73.6	75.1	76.7	90.6
North America	29.9	32.0	39.3	42.7	43.3	44.4	44.9	45.2	46.5	47.7	59.6
World Total	532.2	579.3	746.5	842.3	868.1	884.9	917.5	928.9	969.8	1,012.4	1,218.6

Figure 2-6: Marginal Abatement Cost Curves for Top 5 Emitters in 2030



The MAC illustrates the cumulative abatement achievable at incrementally higher carbon prices. At extremely high break-even prices (> \$500/tCO_2e), the MAC becomes inelastic or unresponsive. The point at which the MAC becomes unresponsive to any price change can also be considered the technical potential associated with the suite of abatement measures considered. Thus, it can be inferred that additional reductions beyond approximately 58% of the projected baseline in 2030 would be unlikely without additional policy incentives or technology improvements.

Economies of scale have an impact on the cost-effectiveness of the abatement options. Hence, abatement measures may have a lower break-even price when applied to facilities with higher CH_4 emission rates and higher break-even price at facilities with a lower emissions rate.

II.2.4.3 Uncertainties and Limitations

Several key areas of uncertainty constrain the accuracy of this analysis. Addressing these uncertainties would improve the development of the MACs and predictions of their behavior as a function of time. Two primary limitations are discussed below.

Improved information on the distribution of emissions in international baselines. This analysis relies on historical activity factors to adjust the distribution of U.S. baseline emissions to develop projections by country. Improvements to information on how gas and oil baselines are changing over time and across segments would improve the accuracy of abatement potential estimates.

Complete information on current abatement technologies used in the gas and oil industry internationally. Additional information on the current and planned implementation of abatement measures internationally would improve the international estimates of abatement.

References

Intergovernmental Panel on Climate Change (IPCC). (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 2 Energy. Chapter 4 Fugitive Emissions.* Obtained from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html.

U.S. Energy Information Administration (EIA). (2011a). *International Energy Outlook 2011*. DOE/EIA—0484(2011). Washington, DC: EIA. Obtained from: http://www.eia.gov/forecasts/ieo/nat_gas.cfm.

U.S. Energy Information Administration (EIA). (2011b). *World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States*. Washington, DC: EIA. Obtained from: http://www.eia.gov/analysis/studies/worldshalegas/.

U.S. Energy Information Administration (EIA). (2011c). *International Energy Statistics: Gross Natural Gas Production.* Washington, DC: EIA. Obtained from: http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=3&pid=3&aid=1.

U.S. Energy Information Administration (EIA). (2011d). *International Energy Statistics: Total Oil Supply.* IEA: Washington D.C. Obtained from: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=53&aid=1.

U.S. Energy Information Administration (EIA). (2012). Country Analysis Brief – Uzbekistan. Washington, DC: EIA. Obtained from: http://www.eia.gov/countries/country-data.cfm?fips=UZ.

U.S. Environmental Protection Agency and Gas Research Institute (USEPA/GRI). (1996). *Methane Emissions from the Natural Gas Industry Volume 2: Technical Report*. EPA-600/R-96-080b. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2003a, October). *Directed Inspection and Maintenance at Gas Processing Plants and Booster Stations*. Lessons Learned from Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2003b, October). *Directed Inspection and Maintenance at Gate Stations and Surface Facilities.* Lessons Learned from Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2006a, October). *Installing Vapor Recovery Units on Storage Tanks*. Lessons Learned From Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2006b, October). *Options for Reducing Methane Emissions from Pneumatic Devices in the Natural Gas Industry*. Lessons Learned From Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2006c, October). *Reducing Methane Emissions from Compressor Rod Packing Systems*. Lessons Learned From Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2006d, October). *Replacing Wet Seals with Dry Seals in Centrifugal Compressors*. Lessons Learned from Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2010). *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry*. Background Technical Support Document. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/emissions/downloads10/Subpart-W_TSD.pdf.

U.S. Environmental Protection Agency (USEPA). (2011a). *Reduced Emission Completions for Hydraulically Fractured Natural Gas Wells*. Lessons Learned from Natural Gas STAR Partners. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2011b). *Oil and Natural Gas Sector: Standards of Performance for Crude Oil and Natural Gas Production, Transmission, and Distribution—Background Technical Support Document for Proposed Standards*. EPA-453/R-11-002. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). (2012a). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). (2012b). *U.S. Greenhouse Gas Inventory Report: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010.* EPA 430-R-12-001. Washington, DC: USEPA. Obtained from: http://epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). (2012c). 2011 Annex 3: Methodological Descriptions for Additional Source or Sink Categories. Sections 3.4 and 3.5. In *2012 U.S. Greenhouse Gas Inventory Report: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009*. EPA 430-R-12-001. Washington, DC: USEPA. Obtained from: http://epa.gov/climatechange/emissions/usinventoryreport.html.

Natural Gas Star Program Lessons Learned Documents Referenced in Model

U.S. Environmental Protection Agency (USEPA). October 2006. Reducing Methane Emissions from Compressor Rod Packing Systems: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Replacing Wet Seals with Dry Seals in Centrifugal Compressors: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Reducing Emissions When Taking Compressors Offline: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Replacing Glycol Dehydrators with Desiccant Dehydrators: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Optimize Glycol Circulation and Install Flash Tank Separators in Dehydrators: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2003. Directed Inspection and Maintenance at Compressor Stations: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2003. Directed Inspection and Maintenance at Gate Stations and Surface Facilities: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2003. Directed Inspection and Maintenance at Gas Processing Plants and Booster Stations: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Replacing Gas-Assisted Glycol Pumps with Electric Pumps: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Using Pipeline Pump-Down Techniques to Lower Gas Line Pressure Before Maintenance: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Composite Wrap for Non-Leaking Pipeline Defects: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Using Hot Taps for In Service Pipeline Connections: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Convert Gas Pneumatic Controls to Instrument Air: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Options for Reducing Methane Emissions From Pneumatic Devices in the Natural Gas Industry: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). (2006a, October). *Installing Vapor Recovery Units on Storage Tanks*. Lessons Learned From Natural Gas STAR Partners. Washington, DC: USEPA. Obtained from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). 2011. Reduced Emission Completions for Hydraulically Fractured Natural Gas Wells: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). October 2006. Installing Plunger Lift Systems in Gas Wells: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). 2011. Options for Removing Accumulated Fluid and Improving Flow in Gas Wells: Lessons Learned from Natural Gas Star Partners. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

U.S. Environmental Protection Agency (USEPA). 2011. Install Electric Motor Starters: Partner Reported Opportunities (PROs) for Reducing Methane Emissions. PRO Fact Sheet No. 105. Washington, DC: USEPA. Obtained on April 2, 2013 from http://www.epa.gov/gasstar/tools/recommended.html.

III. Waste Sector

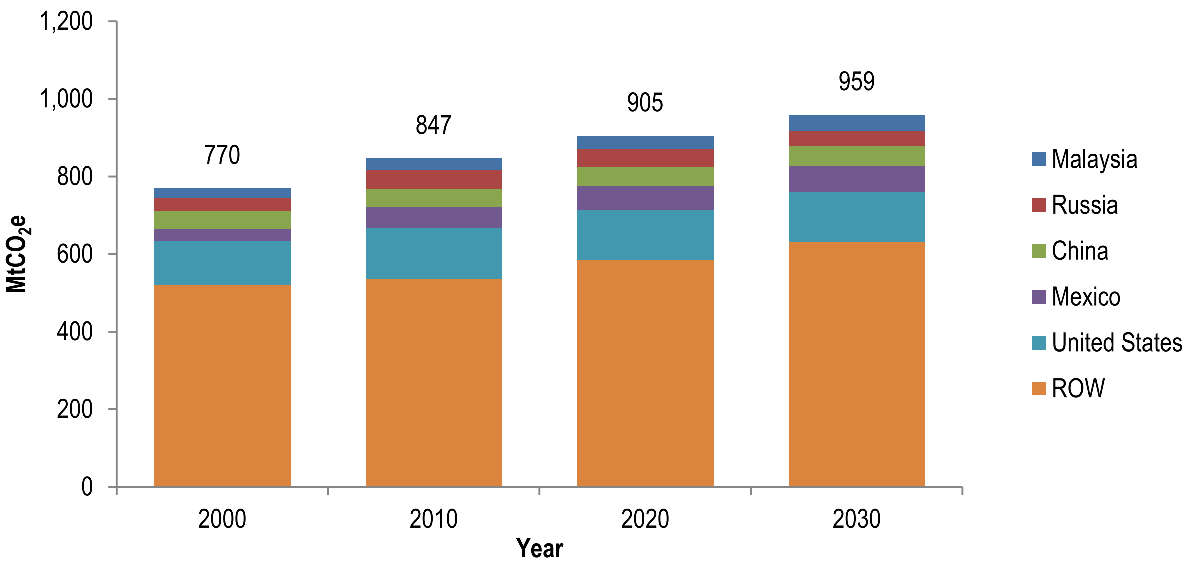
III.1. Landfill Sector

III.1.1 Sector Summary

Landfills produce methane (CH_4) in combination with other landfill gases (LFGs) through the natural process of bacterial decomposition of organic waste under anaerobic conditions. LFG is generated over a period of several decades, with gas flows usually beginning 1 to 2 years after the waste is put in place. CH_4 makes up approximately 50% of LFG. The remaining 50% is carbon dioxide (CO_2) mixed with small quantities of other gases, including volatile organic compounds (VOCs). The amount of CH_4 generated by landfills per country is determined by a number of factors that include population size, the quantity of waste disposed of per capita, composition of the waste disposed of, and the waste management practices applied at the landfill. Changes in these key factors drive projected trends in CH_4 emissions. For a number of countries, LFG is one of the largest anthropogenic sources of CH_4 emissions. Despite efforts to control large landfill emissions, the landfill sector remains a significant source of CH_4 emissions because of increasing waste streams in developed countries. In developing countries, the shift toward sanitary landfills and increased use of abatement measures is a key driver toward CH_4 mitigation.

In 2010, global CH_4 emissions from landfills accounted for approximately 850 $MtCO_2e$. Emissions from landfills are moderately concentrated in several countries. Over 50% of emissions in 2010 come from just ten countries. Figure 1-1 displays the business-as-usual (BAU) emissions for the landfill sector and identifies the top five emitting countries. Landfill emissions are projected to grow 13% between 2010 and 2030. In 2030, emissions from landfills represent 10% of the global total CH_4 from all sources.

Figure 1-1: Emissions Projections for the Landfill Sector: 2000–2030

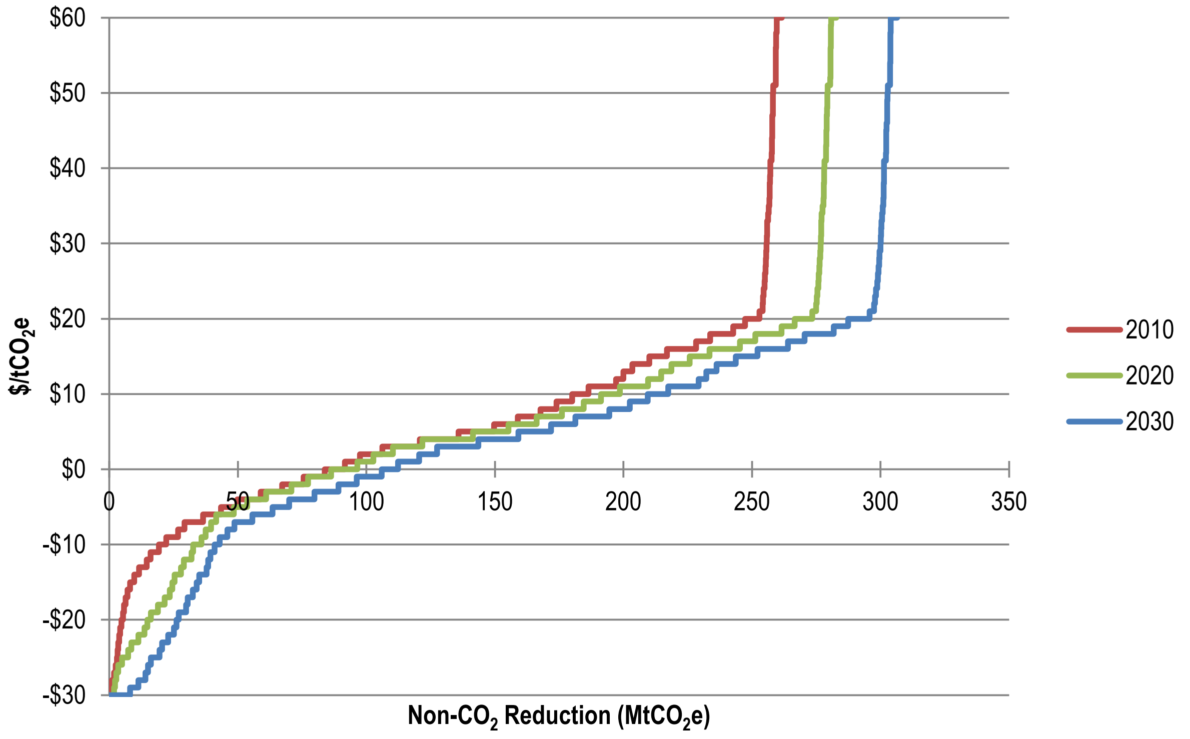


Source: U.S. Environmental Protection Agency (USEPA), 2012

Several abatement measures are available to control landfill CH_4 emissions and they are commonly grouped into three major categories: (1) collection and flaring, (2) LFG utilization systems (LFG capture for energy use), and (3) enhanced waste diversion practices (e.g., recycling and reuse programs). Although flaring is currently the most common abatement measure, energy recovery options may be more cost-effective. Similarly, under favorable market conditions, recycling and reuse or composting alternatives may provide additional means for reducing emissions from landfills. Note that options may not be mutually exclusive in that recycling can reduce the quantity of methane generated, which, in turn, will affect the economics of utilization systems.

Global abatement potential in the solid waste landfill sector is estimated to be approximately 589 $MtCO_2e$ of total annual emissions in 2030, or 61% of the baseline emissions. The marginal abatement cost (MAC) curve results are presented below in Figure 1-2. These curves suggest that there are significant opportunities for CH_4 reductions in the landfill sector at carbon prices below $20. Furthermore there are approximately 70 to 80 $MtCO_2e$ of reductions that are cost-effective (no regret options) at current energy prices.

Figure 1-2: Global Abatement Potential in Landfill Sector: 2010, 2020, and 2030



The following section briefly explains CH_4 emissions from landfills. This is followed by the international baseline CH_4 emissions projections from landfills. Subsequent sections characterize the abatement technologies and present the costs and potential benefits. The chapter concludes with a discussion of the MAC analysis and the regional results.

III.1.2 Methane Emissions from Landfills

This section discusses the characteristics of landfills and how these characteristics affect CH_4 emissions. In this section, we also describe historical and projected trends that influence baseline emissions from municipal solid waste (MSW) landfills. By volume, LFG is about half CH_4 and half CO_2. Typically, LFG also contains small amounts of nitrogen, oxygen, and hydrogen; less than 1% non-CH_4 volatile organic compounds (NMVOCs); and trace amounts of inorganic compounds. The amount and rate of CH_4 generation depend on the quantity and composition of the landfilled material, as well as the site design and resulting physical conditions inside the fill.

Organic waste is initially decomposed by aerobic bacteria after being landfilled. When the oxygen in the landfill cell (section of a landfill) is depleted, the remaining waste is broken down by anaerobic bacteria through decomposition. Fermentation creates gases and short-chain organic compounds that form the substrates, which provide for the growth of methanogenic bacteria, which in turn generates a biogas consisting of approximately 50% CO_2 and 49% CH_4, by volume. Measurable gas volumes are generally available between 1 or 2 years after the waste is landfilled and continue to be generated for 10 to 60 years.

The amount and rate of CH_4 production over time at a landfill depends on five key characteristics of the landfill material and surrounding environment:

- **Quantity of Organic Material:** The quantity of organic material, such as paper, food, and yard waste, is crucial to sustaining CH_4-producing microorganisms. The CH_4 production capacity of a landfill is directly proportional to its quantity of organic waste. CH_4 generation increases as the waste disposal site continues to receive waste and then gradually declines after the site stops receiving waste.
- **Nutrients:** CH_4-generating bacteria need nitrogen, phosphorus, sulfur, potassium, sodium, and calcium for cell growth. These nutrients are derived primarily from the waste placed in the landfill.
- **Moisture Content:** The bacteria need water for cell growth and metabolic reactions to convert cellulose to CH_4. Landfills receive water from incoming waste, water produced by decomposition, surface water infiltration (precipitation), groundwater infiltration (in unlined landfills). In general, CH_4 generation occurs at slower rates in arid climates than in nonarid climates.
- **Temperature:** Warm temperatures in a landfill speed the growth of CH_4-producing bacteria. The temperature of waste in the landfill depends on landfill depth, the number of layers covering the landfill, and the regional climate.
- **pH:** CH_4 is produced in a neutral acidic environment (close to pH 7.0). The pH of most landfills is between 6.8 and 7.2. Above pH 8.0, CH_4 production is negligible.

The methodology for estimating CH_4 emissions from municipal solid waste landfills in this analysis is based on the first order decay model (Intergovernmental Panel on Climate Change [IPCC], 2006).

The key characteristics described above can vary considerably across the different types and features of the waste disposal site, and this, in turn, influences landfill CH_4 generation. This analysis considers abatement measures' impacts on three model facilities representing the solid waste management alternatives with different levels of methane generating capacity. The following are the model facilities considered:

Open dump sites: defined as solid waste disposal facilities where the waste is left uncompacted and without cover. The waste in open dump sites is relatively shallow, therefore promoting aerobic biodegradation. This model facility is particularly relevant to developing countries where solid waste management practices are not well established. These facilities generate relatively small amounts of methane and for this, and safety reasons, have more limited applicability of mitigation technologies, which are less effectiveness where applicable.

Basic landfills (also referred to as managed dump sites): defined as solid waste disposal facilities where the waste is compacted and covered but do not have additional engineered systems. These facilities generate methane and in some cases can be modified to support an oxidation system and/or a gas collection and flaring or energy recovery system. However, the collection efficiency[1] may not be as efficient with a capture efficiency of approximately 75%. These facilities represent the baseline in most developing countries.

Engineered sanitary landfills: defined as facilities that include not only waste compaction and cover but they also are designed and constructed with gas and leachate collection systems. The higher degree of engineering at these facilities generally allows for more efficient gas collection and control than basic sanitary landfills. Engineered landfills typically have a collection efficiency of around 85%. These facilities represent the majority of baseline emissions in major industrialized countries.

III.1.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

This section discusses the historical and projected activity factor data that determine CH_4 generation at solid waste disposal sites and policies set to improve waste management practices. Historical and projected changes in population and household income are used as indicators of changes in the quantity and type of consumption, which are directly linked to the quantity and type of waste generated by countries.

For developing and emerging economies, the projected baseline emissions reflect assumptions about population growth, economic growth, and changes in waste management practices over time in (USEPA, 2012). Continued growth in population along with increased household income and improvements in waste management practices will result in the growth of both waste generated and waste disposed of in managed and engineered landfills.

For developed countries with stable or declining growth in population and income, consumption is assumed to result in only small increases in emissions over time. Developed countries are also assumed to increasingly engage in waste diversion practices (e.g., recycling and composting) that divert biodegradable waste from landfills, ultimately changing the composition of landfilled waste and lowering the annual methane generated over time.

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[1] Collection efficiency refers to the amount of methane generated in the landfill that is captured by the collection system. In contrast, the reduction efficiency refers to the share of collected methane that is destroyed. For example flare have a reduction efficiency of approximately 98%.

III.1.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emission trends globally and presents the baseline emissions used in the MAC analysis.[2]

Historical Emissions Estimates

Emissions from landfills were estimated to have grown by 13% between 1990 and 2010. Key factors that contribute to the growth in landfill emissions include population growth, growth in personal income, increased industrialization, and improvements in waste management practices (USEPA, 2012).

Projected Emissions Estimates

Worldwide CH_4 emissions from landfills are expected to increase at an average long run annual rate of 0.6% (USEPA, 2012). Although some of the largest economies in the world continue to emit significant quantities of CH_4, developing and emerging economies are projected to account for majority of growth in CH_4 emissions. Table 1-1 presents the projected baseline CH_4 emissions for the top five emitting countries and remaining country groups by world region.

Table 1-1: Projected Baseline Emissions for MSW Landfills by Country: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	47.1	48.2	49.0	49.4	49.3	0.2%
Malaysia	29.9	32.5	35.1	37.8	40.3	1.5%
Mexico	56.4	59.5	62.5	65.2	67.7	0.9%
Russia	47.2	46.1	44.8	43.4	42.1	−0.6%
United States	129.7	128.4	127.7	128.0	128.0	−0.1%
Rest of Regions						
Africa	101.2	106.5	111.9	117.3	122.4	1.0%
Central & South America	71.4	74.2	76.8	79.1	81.1	0.6%
Middle East	67.3	72.3	77.1	81.7	86.1	1.2%
Europe	87.2	92.4	96.8	100.9	104.6	0.9%
Eurasia	55.8	58.6	61.5	64.3	66.8	0.9%
Asia	133.2	135.1	138.4	141.5	144.4	0.4%
North America	20.3	21.9	23.3	24.8	26.5	1.3%
World Total	**846.7**	**875.6**	**905.0**	**933.3**	**959.4**	**0.6%**

[a]CAGR = Compound Annual Growth Rate

Source: USEPA. 2012.

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[2] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's Global Emissions Projection Report available at: http://www.epa.gov/climatechange/economics/international.html.

The United States is the largest emitter of landfill CH_4, accounting for over twice the emissions of the second largest emitter, Mexico. Although emissions from the top 4 emitters observed in 2010 are projected to remain relatively constant, emissions from developing regions including Africa, non-Organisation for Economic Co-Operation and Development (OECD) Asia, and the Middle East are all projected to have annual grow rates of greater than 1%. This trend reflects higher population growth rates, changing consumption patterns, and improved waste management systems among developing nations.

III.1.3 Abatement Measures and Engineering Cost Analysis

This analysis considers two types of abatement measures: mitigation technologies and diversion alternatives (see Table 1-2). It is important to note the distinction between these two approaches to emission reductions. Mitigation technologies represent add-on technologies that can be applied to one or more landfill types (i.e., open dump, basic landfill, engineered landfill) intended to capture and destroy the CH_4 generated at the facility. Diverting organic waste from the landfill for alternative uses is the second approach to reduce the quantity of LFG generated at existing landfills. As noted previously, these measures are not mutually exclusive. By changing the composition of waste that is landfilled, diversion options lower the methane-generating potential of remaining waste that is landfilled. Diversion alternatives are covered in this analysis but are distinguished from landfill-based mitigation technologies.

This section discusses the abatement measures considered for this analysis. Each technology is briefly characterized followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis.

Table 1-2: Summary of the Engineering and Cost Assumptions for Abatement Measures at Landfills

Abatement Option	Total Installed Capital Cost (millions 2010 USD)	Annual O&M Cost (millions 2010 USD)	Time Horizon (Years)	Reduction Efficiency (%)[a]
LFG Mitigation Options				
LFG collect and flaring system	1.7	0.3	15	85%
LFG for electricity generation				85%
Internal combustion engine	6.3	0.8	15	85%
Gas turbine (> 3 MW)	5.6	0.6	15	85%
Micro-turbine (< 1 MW)	4.1	0.1	15	85%
Combined heat and power production	7.9	0.8	15	85%
Direct gas use	2.6	0.5	15	85%
Enhanced oxidation systems	5.4	0.0	50	44%
Waste Diversion Options				
Composting	1.8	0.7	15	95%
Anaerobic digestion	16.9	1.7	20	95%
Mechanical biological treatment	15.4	1.8	20	95%
Paper recycling	34.9	8.9	20	95%
Waste to energy	165.7	8.0	20	100%

[a] Reduction efficiency reflects the abatement measures ability to mitigation/avoid methane generation. However this does not reflect the total mitigation potential.

III.1.3.1 Landfill CH_4 Mitigation Technologies

This section characterizes the mitigation technologies that can be applied to landfills to reduce CH_4 emissions. Mitigation options considered for this analysis include collection of LFG for flaring, collection for electricity production, collection for direct use, and enhanced oxidation systems.

LFG Collection and Flaring

Most basic landfills and engineered landfills have (or are applicable for) LFG collection systems for both public health and facility safety concerns to prevent high concentrations of LFG in the fill. These systems prevent the migration of CH_4 to on-site structures and adjacent property and prevent the release of non-CH_4 organic compounds (NMOCs) to the atmosphere. Wells and gathering lines may be constructed in advance or installed after waste has been landfilled. LFG collection usually begins after a portion of a landfill is closed. Collection systems are configured either as vertical wells (which are most common), horizontal trenches (which are primarily used for deeper landfills and landfill cells that are actively being filled), or a combination of the two. Trenches or wellheads are connected to lateral piping that transports the LFG to a collection header. Typically there is a collection system monitor installed to allow operators to adjust the gas flow (USEPA, 2010).

Flares ignite and burn LFG. Large landfills have historically collected CH_4 and flared the gas.[3] Flare designs include open and enclosed flares. Enclosed flares are more expensive but provide greater control of combustion conditions, allow for stack testing, reduce light and noise nuisances, and might have higher combustion efficiencies (USEPA, 2010).

- **Capital Cost:** Capital cost includes the construction of wells, wellheads, and laying of gathering lines that make up the collection system, as well as the flare system with monitoring and control systems. Costs were derived from the USEPA Landfill Methane Outreach Program (LMOP) Project Cost Estimation Model. The capital costs assume one well per acre installed at an average installation cost of $150/ft. Installation of the wellheads and gathering lines is approximately $17,000 per acre. Installed cost of the knockout blower and flare system is based on open flares with the maximum expected flow of LFG per minute ($963/maximum cubic feet per meter [cfm]).
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs for collection systems are $2,250 per well and $4,500 per flare. Electricity costs to operate the blower for a 600 cfm active gas collection system average $44,500 per year[4] (USEPA, 2010), assuming an electricity price of 7 cents/kWh and consumption rate of 0.002 kWh per ft^3.
- **Annual Benefits:** No economic benefits (energy production) are associated with this option.
- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and of 85% for engineered landfills and a flaring efficiency of 98%.
- **Technical Lifetime:** 15 years

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[3] Flares are typically a required component of energy recovery projects. In energy recovery projects, the flare system is used to control LFG emissions during energy generation startups and downtime and may also be used to control excess gas production.

[4] For this analysis we assume an electricity price of 7.5 cents/kWh and an energy consumption rate of 0.002 kWh/ft^3.

LFG Collection for Electricity Generation

Converting LFG to electricity offers a potentially cost-effective way to use the gas being generated by the landfill. Often, revenue from the sale of energy produced can provide a cash flow that more than offsets the implementation costs of this option. This option requires a LFG collection and flare system as described earlier in this section, as well as the electricity generation system. Components of the electricity generation system include the equipment for generating energy (e.g., internal combustion engine, gas turbine, or microturbine) and the interconnections for transmitting electricity produced to the energy grid.

LFG is extracted from landfills using a series of vertical or horizontal wells and a blower (or vacuum) system. This system directs the collected gas to a central point, where it can be processed and treated depending on the ultimate use of the gas. LFG treatment removes moisture and other contaminants (e.g., siloxanes) that may disrupt the energy generation equipment (USEPA, 2010). Treatment requirements depend on the end-use application.

This analysis considers four alternative technologies under this abatement measure that include internal combustion engine, gas turbine, micro-turbine, and combined heat and power (CHP) approach. Table 1-3 summarizes the typical costs for the alternative electricity-generating technologies.

- **Capital Cost:** Capital cost includes the costs of the collection and flare system discussed and the treatment system, energy generation equipment, and interconnection equipment for selling electricity to the power grid. Costs were derived from the USEPA LMOP Project Cost Estimation Model, which is available at USEPA's LMOP web page. Costs ranged from $1,400 to $5,500 per Kwh (see Table 1-3).
- **Annual O&M Cost:** Typical annual O&M costs for energy generation systems are between $130 and $380 per kilowatt of capacity.
- **Annual Benefits:** Annual revenues are derived from the sale of electricity.
- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and 85% for engineered landfills and combustion efficiency of 98%.
- **Technical Lifetime:** 15 years

Table 1-3: Electricity Generation Technology Costs

Technology	Capital Cost (2010 $/kW)	Annual O&M Costs (2010 $/kW)
Internal combustion engine (> 0.8 MW)	$1,700	$180
Small IC engine (< 1 MW)	$2,300	$210
Gas turbine (> 3 MW)	$1,400	$130
Microturbine (< 1 MW)	$5,500	$380
CHP with IC engine (< 1 MW)	$2,300	$210

Source: USEPA 2010. U.S. Environmental Protection Agency (USEPA). September 2010. *Project Development Handbook*. Chapter 3. Project Technology Options. Landfill Methane Outreach Program. Obtained from: http://www.epa.gov/lmop/publications-tools/#one.

Note: Costs include the cost of the basic treatment system typically required with each type of technology.

LFG Collection for Direct Use

Direct use provides an alternative use of LFG with minimal treatment. Under this option, LFG collected at the landfill is pumped to a nearby (< 5 miles) end user. The gas delivered can serve as a medium-BTU fuel for boiler or drying operations, kiln operations, and cement and asphalt production.[5] Although little condensate removal and filtration is needed, combustion equipment might need slight modifications to run with LFG (USEPA, 2010). However these modification costs are not considered part of the technology costs.

There is no cost-effective way to store LFG, so ideally the LFG consumer has a steady annual gas demand compatible with the landfill's gas flow. If a landfill does not have adequate flow, the LFG can be used to power only a portion of the machinery or mixed with other fuels. The cost for a gas compression and treatment system includes compression, moisture removal, and filtration equipment necessary for transporting and using the gas.

- **Capital Cost:**[6] The capital costs for direct use include the equipment and installation cost of a skid-mounted filter, compressor, and dehydrator, and the cost to construct a gas pipeline to carry the gas to a nearby (< 5 miles) end user(s). Filter, compressor, and dehydrator costs are scaled to the project's expected minimum LFG flow and equal to approximately $300 per cfm. Pipeline construction costs are assumed to be $320,000 per mile.
- **Annual Cost:** Annual O&M costs include the cost of electricity and maintenance of the filters, compressors, and dehydrators. The electricity costs are calculated by multiplying electricity price times the energy required to power the equipment and transmit gas to end users, assuming a system power demand of 0.002 kWh/ft^3. Non energy-related O&M costs are scaled to LFG project volumes assuming a cost of $0.0014/ft^3.
- **Benefits:** Annual revenue accrues to the project through the sale of LFG to an end user at an assumed price that is 80% of the current natural gas price; the discounted price reflects the lower BTU content of the gas. There may also be local or national policies such as tax incentives, loans, and grants available to landfill operators to incentivize LFG utilization.
- **Applicability:** This option is available to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumes a collection efficiency of 75% for basic landfills and 85% for engineered landfills and an end-use combustion efficiency of 98%.
- **Technical Lifetime:** 15 years

Enhanced Oxidation Systems

Enhanced oxidation systems are considered mitigation technologies that exploit the propensity of some naturally occurring bacteria to oxidize CH_4.[7] By providing optimum conditions for microbial

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[5] Other direct use applications include use in infrared heaters, greenhouses, artisan studios, leachate evaporation, and biofuel production.

[6] It is important to note that direct use of LFG may require equipment modifications at the end-user site to handle the lower BTU content of LFG or additional treatment systems to improve the energy content; these costs are not considered part of this abatement measure's project costs. Including these costs would increase project costs by more than $200,000 (USEPA, 2010).

[7] Oxidation of methane entails mixing the gas (CH_4) with oxygen (O_2) and converting the CH_4 to CO_2 and water (H_2O).

habitation and efficiently routing landfill gases to where they are cultivated, a number of bio-based systems, such as temporary or long-term biocovers, passively or actively vented biofilters, and biowindows, have been developed that can alone, or with gas collection, mitigate landfill CH_4 emissions. The previous non-CO_2 mitigation report (USEPA, 2006) evaluated the use of a biocover consisting of a clay cap topped by a soil cover.

- **Capital Cost:** Capital costs are the incremental costs of enhanced oxidation systems above the traditional clay/soil cover. These costs assume an incremental cost of $6 million for 100 acres of cover. The cost of designing and constructing the biocover assumes $3/yd^3 for earth moving, a compost price of $5/tonne,[8] and an average cover depth of 3 feet.
- **Annual O&M Cost:** The O&M cost is assumed to be less than 0.1% of installed capital costs.
- **Annual Benefits:** No revenues are associated with this option.
- **Applicability:** This option applies to basic landfills and engineered landfills.
- **Technical Efficiency:** This option analysis assumes a reduction efficiency of 44% of the remaining 15% of methane not collected by LFG collection system (Weitz, 2011).
- **Technical Lifetime:** 50 years

III.1.3.2 Diversion Alternatives

Diversion alternatives redirect biodegradable components of the waste stream from the landfill for reuse through recycling or conversion to a value-add product (e.g. energy or compost). Diverting organic waste components such as yard waste, paper, and food waste lowers the amount of methane generated at the landfill. These measures derive benefits through the sale of recyclables (both organic and non-organic), electricity, and cost savings in avoided tipping fees. Although these options were considered in the previous mitigation report (USEPA, 2006), all diversion options were not included in the final mitigation estimates reported. The following diversion alternatives were considered for this analysis:

- composting
- anaerobic digestion (AD) for electricity production from gas
- mechanical biological treatment (MBT)
- paper recycling
- waste to energy

Composting

Composting consists of the aerobic digestion of the fermentable organic fraction of MSW to produce a reusable product. In the presence of oxygen, microorganisms decompose the biodegradable organic matter to form compost, which contains nutrients and trace elements, and is used in agriculture as soil conditioner. The composting process emits a gas basically formed by CO_2 and H_2O, while traces of (VOCs are also present. This analysis considers three types of composting processes—windrow composting, aerated static pile (ASP) composting, and in-vessel composting—but cost and emissions data were only obtained for windrow composting because it is the most common type.

Windrow composting processes occur in the open, usually in long rows of triangular cross-sections, these being turned periodically to introduce air into the process. The material received by the composters is processed, formed into a windrow, turned (using portable diesel-powered equipment), and screened

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[8] The compost price assumes a weight by volume of 0.32 tonnes/yd^3 (DST Model Documentation).

prior to sale. A typical facility will accept both green material and wood waste from residential curbside programs and an increasing number of composting facilities are beginning to accept food scraps from residential curbside programs, as well as from dedicated commercial routes or large generators. Windrow composting processes may have CH_4 emissions from anaerobic decomposition and nitrous oxides (N_2O) emissions from NO_x denitrification during the latest composting stages. The IPCC (2006) provides representative CH_4 emissions of 4 to 10 g/Kg of waste (dry weight) and N_2O emissions of 0.3 to 0.6 g/kg waste (dry weight).

- **Capital Costs**: Capital cost includes the purchase of land and equipment, site preparation and facility construction equal to $1.8 million (2010 USD). Capital costs were obtained from the composting process model documentation of the Municipal Solid Waste Decision Support Tool (MSW DST) (MSW DST Documentation), which presents this cost for 100 tons/day facilities producing marketable high-quality compost products as opposed to nonmarketable, low-quality compost product (e.g., used as landfill cover).
- **Annual Cost:** The O&M cost of the windrow composting facility includes the labor, overhead, fuel, electricity, and equipment maintenance costs.[9] This analysis assumes an O&M cost of $19/tonne-yr (obtained from the composting process model documentation of the MSW DST (MSW DST Documentation).
- **Annual Benefits:** Revenue from compost is from sales and cost savings from avoided landfilling. The composting process is not perfectly efficient, and this analysis assumes that 80% of the incoming organic waste is converted to marketable compost product. A compost price of $5/tonne[10] was used to estimate the revenue from compost sales. A tipping fee of $29/tonne is used to estimate the costs savings of avoided landfilling.
- **Applicability:** This option applies to yard and food components of the waste stream.
- **Technical Efficiency:** This analysis assumes reduction efficiency of 95%, which represents the avoided methane potential.
- **Technical Lifetime:** 15 years

Anaerobic Digestion (AD)

AD is a complex biological process that uses anaerobic microorganisms to hydrolyze complex organics to simple monomers and hence to volatile fatty acids; the volatile fatty acids are converted to CH_4 and CO_2 in the biogasification step. The biogas can be recovered and used to generate energy. Existing AD facilities are most commonly located at wastewater treatment plants, but the process is equally applicable for solid waste. A few of these facilities supplement their operations with other types of organic waste.

Solid waste AD facilities come in different shapes and sizes. Most digesters have vertical tanks, but some are horizontal. AD mechanisms vary considerably, and a number of patented processes exist. Processes may operate at high or low solids content, operate at mesophilic or thermophilic temperatures, be one- or two-stage systems, and be continuous or batch processes. The process could also differ

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[9] This analysis assumes that no precomposting screening will take place. Therefore, there will not be organics rejects from the process needing disposal at a landfill facility, which is consistent with the data provided for high quality compost production in the composting process model documentation of the MSW DST (MSW DST Documentation).

[10] Represents the lower end price $15 to 34/yard^3 assuming a 0.35 tonne/yard^3. Prices reported in Recycle.cc's December 2011 newsletter. Obtained at: http://www.recycle.cc/compostprices.pdf

according to the type of product produced, so some processes only produce electricity, others produce combined electricity and heat, and some produce gas upgraded for use as vehicle fuel. This analysis considers AD that produces electricity using a gas engine, which is the most common product. A small amount of CH_4 may be released as fugitive emissions during the digestion process. This analysis assumes CH_4 emissions of 1 to 2 g/kg of waste (dry weight) as reported in IPCC (2006).

- **Capital Costs**: The plant's capital cost includes the cost of land, the digestors, the gas engine, and air pollution control and monitoring devices. The capital cost for this analysis is $472/design tonne was considered in this analysis and obtained from Eunomia (2008), which describes this cost for facilities of 20,000 to 30,000 tonnes/yr in the United Kingdom (UK).
- **Annual Cost:** The O&M cost of the AD facility includes the labor, overhead, fuel, electricity, and maintenance cost. An O&M cost of \$55/tonne yr^{-1} (reported as £35 GBP/tonne) was considered in this analysis and obtained from Eunomia (2008), which presents costs typical of UK facilities. This analysis assumes that no predigestion screening will take place and that the digested solids are not commercialized. Therefore, there will be no organics rejects from the process needing disposal at a landfill facility.
- **Annual Benefits:** Revenue from the sale of electricity generated with the biogas is sold to an end user. The biogas recovery from the digestion process is not perfectly efficient and assumed to be 75% of total value, and the biogas composition is assumed 60/40% CH_4/CO_2 according to Eunomia (2008). Similarly, the efficiency of the biogas conversion to electricity in the gas engine is assumed to be 37% as reported by Eunomia (2008). The electricity produced per tonne of waste can be then estimated according to the CH_4 yield (2,781 ft^3 CH_4/wet ton) of the incoming waste. The market price of electricity is used to estimate the revenues.
- **Applicability:** This option assumes removal of wood, paper, and food waste.
- **Technical Efficiency:** This analysis assumes a capture efficiency of 75% and a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years

Mechanical Biological Treatment (MBT)

MBT can be defined as the processing or conversion of solid waste with biologically degradable components via a combination of mechanical and other physical processes (for example, cutting or crushing, sorting) with biological processes (aerobic composting, anaerobic digestion). The primary objective is to reduce the mass and the volume of the waste. A secondary objective is a lower environmental impact of the waste after its deposition (i.e., low emissions of landfill gas, small amounts of leachate, and a reduced settlement of the landfill body). Furthermore, MBT includes the separation of useful waste components for industrial reuse, such as metals, plastics, and refuse-derived fuel (RDF).

There are three main types of biological treatment processes: (1) an aerobic stabilization system in which the stabilized output is assumed to be sent to a landfill or used for land remediation/recovery projects, (2) an aerobic biodrying system producing an RDF with the reject stream sent to a landfill (after undergoing an aerobic stabilization process), and (3) systems combining aerobic and anaerobic treatments in which the anaerobic process is used to produce biogas, followed by an aerobic process that produces a stabilized output that can be sent to a landfill. Because of the similarities that can be found between Option (1) and composting, and Option (3) and AD, this analysis focuses on Option (2) in which the RDF is destined for energy generation.

To produce RDF, both windrow and box systems are applied. In box systems, the waste is treated aerobically for only 1 week but with high aeration rates. The result is a dried material with a slightly reduced organic content. Only the most easily degradable compounds are metabolized so that the loss of caloric value is low. The dry material can be fractionated very easily, because adhesive substances were eliminated in the bio-process. Iron and nonferrous metals, as well as glass and minerals, are separated for material recovery. The remaining material has a calorific value of 15 to 18 MJ/kg, mainly due to the high content of plastics, wood, and paper. It can be used as a substitute for fossil fuels in power stations and cement kilns and in the production of process gases. Similar to the composting process, there is a small level of fugitive CH_4 emissions that accompany the aerobic degradation process as well as some N_2O emissions from NO_x denitrification during the curing stages of the stabilization process. Representative CH_4 emissions of 0.01 kg/tonne of waste and N_2O emissions of 0.02 kg/tonne of waste were obtained from Eunomia (2008).

- **Capital Costs**: The plant's capital cost includes the cost of land, facility, equipment, and air pollution control and monitoring devices. The analysis assumes a capital cost of $15 million based on reported facility costs of $244/design tonne (reported as £150 British pounds/tonne) was used for this analysis and obtained from Eunomia (2008). Costs are reported for a 60,000 tonne/yr facility in the UK.
- **Annual O&M Costs:** The O&M cost of the MBT facility is $2 million in 2010. This cost includes the labor, overhead, taxes, administration, insurance, indirect costs, energy, and maintenance costs. It does not include residues disposal. A 2007 annual O&M cost of $22/tonne (reported as £13 British pounds/tonne) was considered in this analysis and obtained from Eunomia (2008), which presents costs typical of UK facilities.
- **Annual Benefits:** Annual revenues from the sale of RDF and recyclables that are produced from the MBT process are sold to an end user (i.e., cement kilns or coal-fired utility). According to Eunomia (2008), RDF is produced at a typical rate of 0.48 tonne/tonne of waste. Eunomia (2008) also reports that 1 tonne of RDF can be assumed to replace 0.90 tonne of coal used to fuel a cement kiln and 0.38 tonne of coal for power generation. The market coal price of $40/tonne is used to estimate the revenues. Similarly, Eunomia (2008) reports an 80% recovery rate for ferrous metals, 70% recovery rate for nonferrous metals, and 70% recovery rate for glass. Sale prices of $352/tonne for ferrous metals (USGS, 2012), $1,881/tonne[11] for nonferrous metals, and $25/tonne for glass were used to estimate the revenues from recyclables sale.
- **Applicability:** This option applies to all landfill types
- **Technical Efficiency:** This analysis assumes a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years

Paper Recycling

Recycling typically consists of two major processes: the separation process at a material recovery facility (MRF) and the remanufacturing process where recyclables are used to produce new products. For consistency with other mitigation option included in this report, the costing component of this analysis only considers the separation process. The different types of MRFs vary according to the type of waste they receive and the destination of the recyclables (e.g., mixed waste MRF, commingled recyclables MRF, presorted recyclables MRF, co-collection MRFs, and front-end MRFs to other waste diversion alternatives such as composting). Because it is the most common, this analysis considers a mixed waste MRF.

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[11] Price obtained from MetalPrices.com at http://www.metalprices.com/FreeSite/metals/al_scrap/al_scrap.asp#Tables.

Under the mixed waste MRF design, mixed waste is typically collected at curbside and dumped on a tipping floor at the MRF. It is then loaded onto a conveyer by using a front-end loader or Bobcat. This conveyer feeds a bag opening station because most waste is collected in bags. Undesirable items in the waste (e.g., white goods, bulky items) are removed from the mixed waste before and after the bag opening point in the MRF. Bags can be opened either manually or mechanically, and this analysis considers mechanical bag opening. Loose waste from the bag opening operation is then conveyed into an elevated and enclosed sorting room where the recyclables are recovered. Newsprint, old corrugated cardboard, and other paper can be picked from the mixed waste as individual components. Because other paper components are present in small quantities and are likely to be wet and contaminated, they can only be recovered as mixed paper. Metal cans remain in the refuse on the conveyer at the end of the sort room. Separation of aluminum cans can be manual or automated, and this analysis assumes manual separation. Ferrous metal is assumed to be recovered by a magnet.

Apart from power consumption, no residual greenhouse gas (GHG) emissions are assumed, and the MRF facility costs are divided into three components: capital cost, O&M cost, and revenue from recyclables sale.

- **Capital Costs**. The capital cost for this option is $35 million in (2010 USD). The capital cost consists of construction, engineering, and equipment costs. It assumes a handling capacity of 100,000 tonnes of waste per year. This analysis relies on a $297/tonne of annual capacity (2006 prices), which is an average of reported capital costs from CalRecycle (2009) for similar sized facilities.
- **O&M Cost**. The O&M cost of the MRF facility includes wages, overhead, equipment and building maintenance, and utilities. An O&M cost of $66/tonne of annual waste capacity before residue disposal, based on reported operating costs used in CalRecycle (2009) report. The cost of disposal of the MRF rejects can be estimated assuming an MRF separation efficiency of 55% of the incoming organic waste and that the rejects are sent to a regular landfill with a tipping fee of $29/tonne, which represents a U.S. national average tipping fee obtained from *Municipal Solid Waste Facility Directory* (Chartwell, 2004).
- **Annual Benefits:** Annual benefits come from the sale of recyclables and decreased waste. The recyclables that are separated at the MRF are sold to an end user (e.g., a remanufacturing facility) sometimes through brokers. The 55% separation efficiency and recyclables sale prices were used to estimate the revenues from recyclables sale. The following prices were used in the analysis: mixed paper[12]—$140/tonne; scrap metals[13]—$1,307/tonne; and scrap glass—$25/tonne. Tonnage sold for reuse avoids landfilling costs. Annual cost savings are equal to tonnage sold for reuse times the tipping fee of $29/tonne.
- **Applicability:** This option applies to the entire waste stream.
- **Technical Efficiency:** This analysis assumes a reduction efficiency of 95% of potential methane.
- **Technical Lifetime:** 20 years

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[12] Prices were obtained from: http://www.recycle.cc/freepapr.htm.

[13] Assumes a weighted average price of aluminum can scrap and ferrous metal scrap prices. The aluminum can scrap price was obtained from http://www.metalprices.com/. The ferrous metal price was obtained from 2012 USGS *Mineral Commodities Summary: Iron & Steel Scrap* at: http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_scrap/.

Waste-to-Energy (WTE)

WTE is a combustion process; thus, its main emissions include CO_2, CO, NO_x, and non-CH_4 volatile organic compounds (NMVOCs). Municipal waste is incinerated to reduce its volume to save landfill costs and recover energy from its combustion either for heating and/or electricity generation. The two most widely used and technically proven incineration technologies are mass-burn incineration and modular incineration. Fluidized-bed incineration has been employed to a lesser extent, although its use has been expanding and experience with this relatively new technology has increased. RDF production and incineration have also been used, primarily in Europe, but the number of successful cases is limited. This analysis considers WTE using mass-burn incineration and electricity recovery, which is the most common WTE design. Representative CH_4 emissions of 0.2 to 60 kg/Gg of waste (wet weight) and N_2O emissions of 41 to 56 g/ton of waste (wet weight) were obtained from IPCC (2006). WTE facility costs are divided into three components: capital cost, O&M cost, and revenue from electricity generation.

- **Capital Costs**. The plant's capital cost of $165 million includes the facility design engineering and construction. Capital equipment includes the cost of land, incinerators, ash handling system, turbine, and air pollution control and monitoring devices. Costs assume $829/tonne of design capacity. This cost was derived from Eunomia (2008), which describes this cost for a 200,000 tonne/yr facility in the UK.
- **O&M Cost**. The annual O&M cost of the WTE facility is $8 million, approximately 4% of installed capital costs. Annual costs include labor, overhead, taxes, administration, insurance, indirect costs, auxiliary fuel cost, electricity cost, and maintenance cost. It does not include the cost for disposing of the combustion residue and spray dryer residue. Cost is based on annual O&M cost of $41/tonne/yr. Annual avoided landfilling is also included as a cost savings. The cost of disposal of the fly and bottom ash from the incineration process assumes an estimated 15% of the incoming organic waste will be converted to ash (MSW DST Documentation). No reuse of the bottom ash (e.g., in construction projects) is assumed and the bottom and fly ash will be mixed and sent to a landfill. Both the avoided landfilling costs and residual waste landfilling costs assume a tipping fee of $29/tonne.
- **Annual Benefits:** Annual revenue from electricity sales. Electricity that is generated by recovering heat from combusting waste is sold to an end user. The recovery of the heat is not perfectly efficient. This inefficiency is represented by the heat rate of the plant, reported as 18,000 (BTU/kWh) in the WTE process model documentation of the MSW DST (MSW DST Documentation). The electricity produced per tonne of waste can then be estimated according to the heat value of the waste incinerated (4,750 BTU/tonne of waste). The market price of electricity is used to estimate the revenues.
- **Applicability:** This option applies to entire waste stream.
- **Technical Efficiency:** This analysis assumes reduction efficiency of 100%.
- **Technical Lifetime:** 20 years

III.1.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in above to compute the net cost/benefit of abatement for each project. Similar to the approach used in other non-CO_2 sectors of this report, we compute a break-even price for each abatement project (abatement measure by facility type). Project break-even prices are then weighted by emission abatement potential to construct MAC curves illustrate the technical, net GHG mitigation potential at specific break-even prices for 2010 to 2030. MAC curves are produced for 195 countries using country specific parameters, such as wage rates and energy prices.

This section describes the general modeling approach applied in the landfill sector as well as the approach used to define the international facility populations and the assessment of sectoral trends. These factors serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

III.1.4.1 Methodological Approach

The overarching modeling framework applied in the landfill sector is captured in two basic steps. The first is to calculate the break-even price for each mitigation measure for each facility type by country. The second is to determine the country-level abatement potential.

The break-even price, as defined in the technical summary to this report, estimates the costs and expected benefits of each technology based on the characteristics of the model facility and relative international prices (equipment, labor, and energy).

Country abatement potential reflects the number of abatement measures available and technical effectiveness of each option. Figure 1-3 illustrates the conceptual modeling for estimating the abatement potential in the landfill sector.

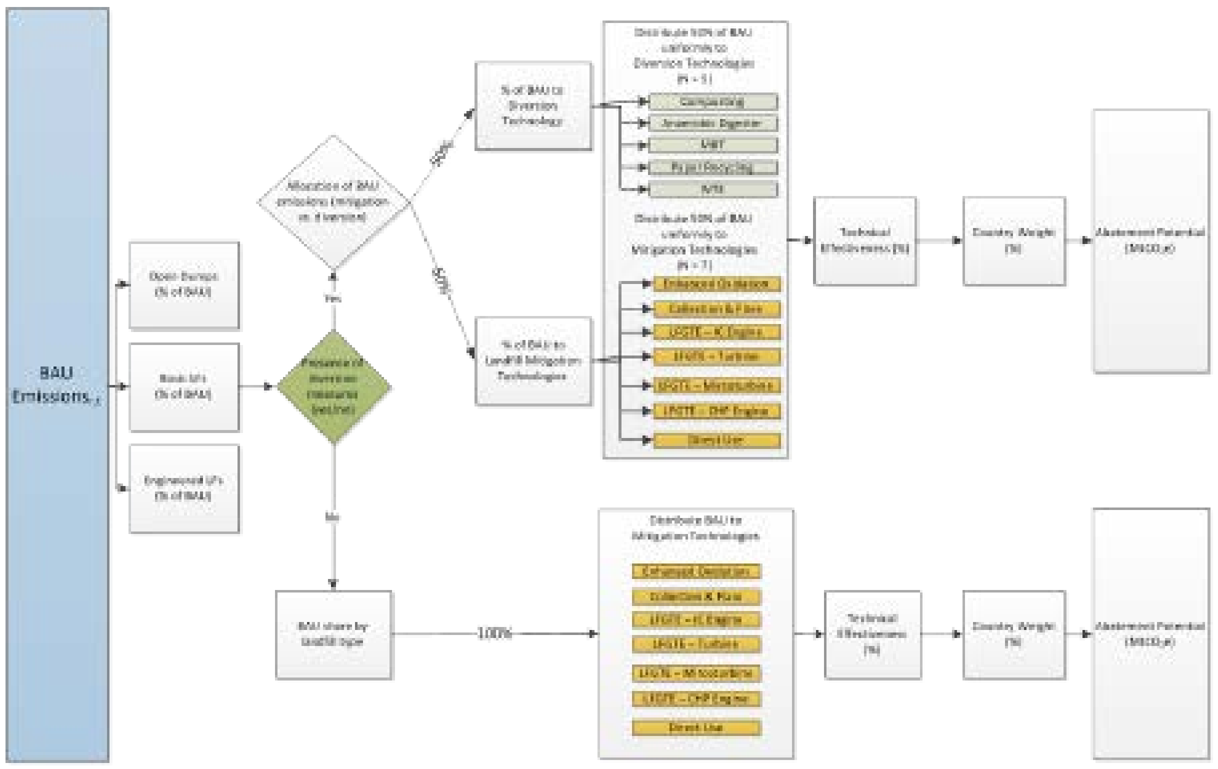
The MAC model uses a three-step approach to allocating a fraction of the BAU emissions to each facility and technology considered. The model starts by splitting the BAU emissions out to our three landfill types (open dump, basic landfill, engineered landfill). Next the model uniformly distributes BAU emissions by the number of abatement measures considered. Finally, the model estimates abatement potential by multiplying the BAU emissions (indexed by facility type and technology) by each technology's technical effectiveness. Summing over all abatement measures and facility type indicates this product yields a country's abatement potential.

It is important to note that depending on the scenario considered in the model, diversion options may or may not be included. As shown in Figure 1-3, if diversion options are considered, BAU emissions (indexed by facility type) are uniformly distributed by the total number of technologies (N = 12). If diversion options are omitted, BAU emissions are distributed by the number of landfill-based mitigation technologies (N = 7).

Assessment of Sectoral Trends

Underlying the general modeling approach, the MAC analysis also incorporated additional international considerations to capture shifts in the share of BAU emissions allocated to the three model landfill types defined earlier in Section III.1.2 (i.e., open dump, basic landfill, and engineered landfill). Table 1-4 presents the facility share of BAU emissions over time. In the United States and the EU, we assumed advanced waste management practices were already in place. Reflecting this assumption, we assumed zero emissions coming from open dumps in these countries and assumed all emissions come from basic and engineered landfills. Given the existing level of infrastructure in place there is very little change in the assumed distribution over the 20-year modeling horizon.

Figure 1-3: Conceptual Model for Estimating Mitigation Potential in the MSW Landfill Sector



For emerging economies and developing countries the analysis assumes a greater share of emissions is represented by open dumps in 2010. Over the next 20 years, this distribution is projected to shift away from open dumps as countries begin to adopt advanced waste management practices with greater shares of total waste going to basic sanitary and engineered landfills. These shares were developed using expert judgment after reviewing existing literature on waste disposal trends and abatement opportunities provided through various studies by the World Bank, USEPA's LMOP program, and the Global Methane Imitative (GMI).

Define Model Facilities for the Analysis

Seeking to improve the specificity of the break-even prices calculated for each country, this analysis developed an international population of model facilities. This step of the analysis consisted of defining the characteristics of the model facilities specific to countries and regions. The characteristics of interest included the

- average annual waste acceptance rates by facility type,
- average waste depth by facility,
- decay constant (k) based on climate and moisture content in waste landfilled, and
- potential CH_4 generation capacity (L_0) of the typical waste managed in a given model facility.

Table 1-4: Model Facilities Share of BAU Emissions: 2010–2030

Country/Region	2010			2020			2030		
	Dump Sites	Basic LF	Engineered LF	Dump Sites	Basic LF	Engineered LF	Dump Sites	Basic LF	Engineered LF
China	20%	60%	20%	10%	60%	30%	10%	50%	40%
Brazil	10%	60%	30%	10%	50%	40%	0%	50%	50%
Mexico	10%	60%	30%	10%	50%	40%	0%	50%	50%
Russia	20%	40%	40%	20%	40%	40%	10%	40%	50%
Ukraine	20%	40%	40%	20%	40%	40%	10%	40%	50%
Australia	10%	30%	60%	10%	30%	60%	0%	30%	70%
Canada	10%	30%	60%	10%	30%	60%	0%	30%	70%
Japan	10%	30%	60%	0%	30%	70%	0%	20%	80%
Turkey	20%	40%	40%	20%	40%	40%	10%	40%	50%
United States	0%	20%	80%	0%	20%	80%	0%	10%	90%
India	20%	60%	20%	10%	60%	30%	10%	50%	40%
South Korea	10%	30%	60%	0%	30%	70%	0%	20%	80%
EU-27	0%	20%	80%	0%	20%	80%	0%	10%	90%
Africa	40%	40%	20%	30%	40%	30%	20%	40%	40%
Central & South America	10%	60%	30%	10%	50%	40%	0%	70%	30%
Middle East	20%	60%	20%	10%	60%	30%	10%	60%	30%
Eurasia	20%	60%	20%	10%	60%	30%	10%	60%	30%
Asia	20%	60%	20%	10%	60%	30%	10%	60%	30%

Source: Based on expert judgment in consultation with World Bank (2010) and USEPA (2009, 2011).

Various data sources were consulted to define the characteristics of the model facilities in the different countries and regions, and a proxy country approach was used when data were not found for a given country. Under this approach, countries for which no data were available were paired with a representative proxy country based on similarities in socioeconomic and technology development trends that are closely correlated with a country's waste composition. Furthermore, waste composition is the only parameter that affects both L_0 (CH_4 generation rate) and k constant (decay rate), two key factors used to estimate gas generation from the model facilities.

To ensure project costs and benefits were comparable, we assumed annual waste acceptance rates (WAR) were fixed at 100,000 tonnes/yr, and the average depth of waste was assumed to be between 25 and 50 feet. Open dumps have shallower waste depths sprawling over large areas. In contrast, basic and engineered landfills concentrate the disposed waste over a smaller area and at increased depths of between 40 and 50 feet. Facility methane recovery (also referred to as capture efficiency), also varies by landfill type and range from 10% for open dumps to 85% for engineered landfills. Table 1-5 summarizes the standardized model facility assumptions.

Table 1-5: Model Facility Assumptions for International LFG Mitigation Options

Facility Type	No. Years Open	Annual WAR (tonnes/yr)	Project Design Acreage	Waste Depth (ft)	Facility CH_4 Recovery
Engineered landfill	15	100,000	40	50	85%
Basic landfill	15	100,000	50	40	75%
Open dump	15	100,000	80	25	10%

To improve the heterogeneity in the break-even options across countries, we developed a dataset of country-specific data of L_0 (methane generation potential) and k constant (decay rate) values, the two key parameters in the first order decay model, which is used to estimate landfill gas generation. Both parameters were calculated based on the composition of the waste being landfilled, which is determined by the country-specific socioeconomic conditions, consumption patterns, and waste management practices. Therefore, the methane generation results and, consequently, the amount of methane potentially mitigated by each landfill gas control measure are driven by the waste composition, which is related to consumption patterns and socioeconomic conditions. We grouped the countries according to the following logic:

First, we identified the decay constant (k) and CH_4 generation potential of waste (L_0) for 16 countries that included at least 1 country within the each major region (Africa, Asia, Caribbean/Central & South America, Eurasia, Europe, Middle East, and North America). This information was obtained from a number of sources, including international studies conducted by the World Bank, USEPA's voluntary program, the MSW Decision Support Tool (DST), and other peer-reviewed literature.

Second, we then used expert judgment, taking into consideration trends of socioeconomic and technological development to associate countries with other countries for which we have methane generation data (e.g., we have methane generation data for Jordan and considered that Algeria, Egypt, and South Africa have similar socioeconomic and technological conditions). Alternatively, we have methane generation data for Guinea, but we think that the socioeconomic and technological conditions in Egypt, Algeria, and South Africa are closer to those in Jordan than to those in Guinea.

Table 1-6 presents the data used to characterize the model facilities for specific countries identified for this analysis.

The international assessment of other OECD countries assumes waste management practices and landfill designs similar to those in the United States. For this reason, we leverage the existing United States-based landfill population, scaling the landfill size and emissions to meet projected baselines. For all non-OECD countries for which we had no data, we developed three model facilities to represent the allocation of waste to each type of waste management facility (i.e., engineered landfill, sanitary landfill, and open dump). Each facility type was assumed to have similar characteristics in terms of capacity, average depth of waste in place, and annual waste acceptance rates.

Table 1-6: CH_4 Generation Factors by Country

Country	Region[1]	k Constant (1/yr)	L_0 (ft^3/short ton)	Data Source
Guinea	Africa	0.18	4,690	WB
China	Asia	0.11	1,532	LMOP
India	Asia	0.11	3,988	Zhu et al. (2007)
Japan	Asia	0.11	4,620	WB
Nepal	Asia	0.04	6,890	WB
Pakistan	Asia	0.11	3,193	WB
Philippines	Asia	0.18	1,922	MSW DST
Argentina	CCSA	0.11	4,122	WB
Belize	CCSA	0.12	2,499	MSW DST
Colombia	CCSA	0.11	2,948	LMOP
Nicaragua	CCSA	0.11	2,627	MSW DST
Panama	CCSA	0.11	3,236	MSW DST
Bosnia and Herzegovina	Eurasia	0.06	4,295	WB
Ukraine	Eurasia	0.06	4,886	LMOP
Jordan	Middle East	0.02	5,984	WB
United States	North America	0.04	3,055	LMOP

[1] CCSA = Central & South America

Sources: WB—World Bank Studies by Country; LMOP—USEPA's LMOP country-specific landfill gas models; MSW DST—decision support model; and Zhu et al. (2007) "Improving municipal solid waste management in India."

Estimate Abatement Project Costs and Benefits

This analysis leveraged the USEPA *LFG to energy project costs model* to estimate abatement project costs and benefits for the landfill-based mitigation technologies (with the exception of enhanced oxidation). Key model facility characteristics discussed above were used as inputs to estimate the project costs across countries. For waste diversion alternatives, we assumed that waste was diverted from landfills and sent to alternative facilities for separation and reuse. Any residual waste from these facilities is then sent to a landfill for final disposal. Model facilities reflect the recycling or reuse facility's annual waste processing capacity as described in Section III.1.3.2.

Table 1-7 and Table 1-8 provide example break-even prices for model landfills and diversion facilities using U.S. parameters and costs.

Table 1-7: Example Break-Even Prices for MSW Landfill Technology Options

Option by Landfill Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Annual Tax Benefit of Depreciation ($/$tCO_2e$)	Break Even Price ($/$tCO_2e$)
Open Dump						
Direct use	7,475	$50	$28	$11	$10	$57
Combined heat and power	7,475	$86	$31	$10	$17	$89
Engine	7,475	$55	$30	$10	$11	$64
Microturbine	7,475	$54	$31	$7	$11	$67
Turbine	7,475	$57	$29	$8	$12	$66
Flare	7,475	$38	$27	$0	$8	$58
Basic Landfill						
Direct use	56,061	$6	$4	$11	$1	−$2
Combined heat and power	56,061	$17	$6	$10	$4	$10
Engine	56,061	$12	$6	$10	$2	$6
Microturbine	56,061	$11	$4	$7	$2	$6
Turbine	56,061	$13	$5	$8	$3	$7
Flare	56,061	$4	$3	$0	$1	$6
Engineered Landfill						
Direct use	63,536	$5	$4	$11	$1	−$4
Combined heat and power	63,536	$16	$6	$10	$3	$8
Engine	63,536	$11	$5	$10	$2	$4
Microturbine	63,536	$10	$3	$7	$2	$4
Turbine	63,536	$12	$4	$8	$3	$6
Flare	63,536	$3	$2	$0	$1	$5

Note: Based on USA CH_4 generation parameters: L_0 = 3,204 and k = 0.04. Assuming model landfill standardized size assumptions from Table 1-5. Break-even price is calculated using a discount rate of 10% and a tax rate of 40% and assumes energy prices of $3.2/Mcf and $0.07/kWh for gas and electricity.

Table 1-8: Break-Even Prices of Waste Diversion Options

Waste Diversion Options	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Annual Tax Benefit of Depreciation ($/$tCO_2e$)	Break Even Price ($/$tCO_2e$)
Composting	5,222	$119	$121	$185	$24	$31
Anaerobic digestion	4,658	$1,626	$360	$330	$277	$1,380
Mechanical biological treatment	18,605	$414	$68	$263	$70	$148
Paper recycling	6,164	$1,613	$1,249	$1,028	$275	$1,559
Waste to energy	55,816	$2,247	$142	$284	$383	$1,722
Enhanced oxidation systems	10,483	$143	$1	$0	$11	$132

Note: Assuming model sizes as described in Section III.1.3. Present values calculated using a discount rate of 10% and a tax rate of 40%.

III.1.4.2 MAC Analysis Results

The MAC curve results are presented in Table 1-9 and Figure 1-4 by major emitting country and rest of regional country groups. The MAC curves illustrate the increase in abatement achievable at higher carbon prices. In 2030, the MAC curves show that approximately 589 $MtCO_2e$, or 61% of global baseline CH_4 emissions from landfills, can be abated by adopting mitigation and avoidance options presented in Section III.1.3.

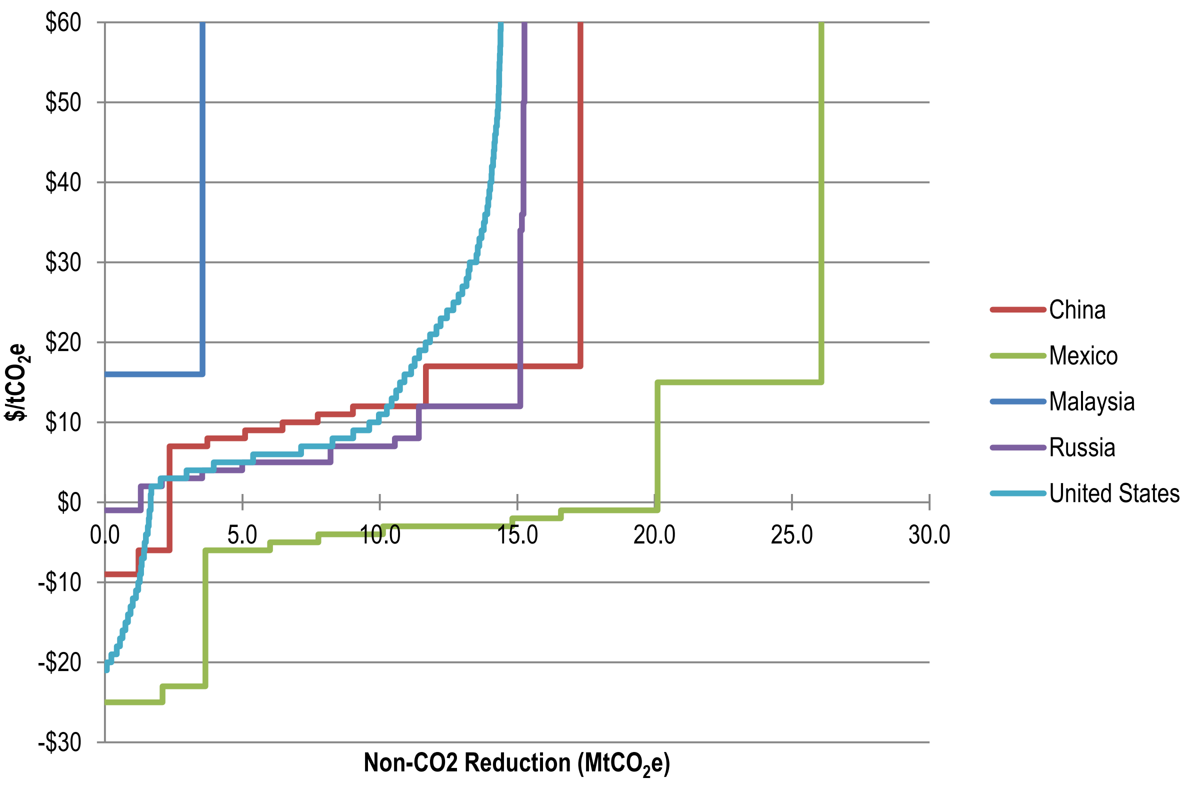
Approximately 112 $MtCO_2e$, or 19% of global abatement potential has a break-even price of zero or less. These mitigation options are sometimes referred to as "no regret" options because the benefit cost analysis implies that they would have a positive return. However, as discussed previously, there may be transaction costs not captured in this analysis that are currently limiting their adoption.

At break-even prices between $20/$tCO_2e$ to $50/$tCO_2e$ most countries MAC curves become non responsive (vertical). This is because there are few options within this break-even range. Between $50/$tCO_2e$ to $100/$tCO_2e$ an additional 20% of abatement potential becomes economically viable. And, at break-even prices (> $100/t CO_2e) the remaining set of emission reduction options are economically viable, but at extremely higher prices. The point at which the MAC becomes unresponsive to any price change can also be considered the full technical potential associated with the suite of abatement measures considered. Thus, it can be inferred that additional reductions beyond approximately 60% of the projected baseline in 2030 would be unlikely without additional policy incentives or technology improvements.

Table 1-9: Abatement Potential by Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($/$tCO_2e$)										
Country/Region	10	5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China		2.4	2.4	2.4	9.0	11.7	17.3	17.3	17.3	23.8	37.0
Malaysia						3.5	3.5	3.5	3.5	8.7	19.6
Mexico	3.7	7.8	20.1	20.1	20.1	26.1	26.1	26.1	26.1	34.8	53.0
Russia			1.3	8.2	11.4	15.1	15.1	15.1	15.3	20.7	32.0
United States	1.3	1.5	1.7	7.1	10.3	11.1	12.1	13.6	14.3	14.5	14.6
Rest of Region											
Africa	5.6	5.6	5.6	9.7	26.1	31.3	42.7	42.7	43.2	60.3	95.4
Central and South America	1.6	4.4	8.7	8.8	8.8	9.1	16.3	16.4	16.4	27.6	50.9
Middle East	3.5	4.0	7.5	20.1	20.8	23.2	25.0	26.3	27.0	36.2	55.7
Europe	22.8	36.0	49.0	70.9	82.6	86.7	91.8	92.7	93.1	98.8	110.4
Eurasia						1.6	2.3	2.3	2.3	5.8	12.9
Asia	2.9	6.7	11.8	15.8	17.5	19.1	29.7	30.1	30.1	48.7	86.3
North America	1.5	1.6	4.2	8.7	10.8	13.6	13.8	14.0	14.1	15.0	21.5
World Total	**43.0**	**70.0**	**112.4**	**171.9**	**217.4**	**252.2**	**295.7**	**300.1**	**302.8**	**394.9**	**589.4**

Figure 1-4: Marginal Abatement Cost Curve for Top 5 Emitters in 2030



III.1.4.3 Uncertainties and Limitations

Uncertainty and limitations persist despite attempts to incorporate all publicly available information. Additional country-specific detailed information would improve the accuracy of the MAC projections.

- Energy prices are negotiated on a case-by-case basis and may not be as high as the wholesale price used in the analysis.
- National/regional or local policies for permitting projects may differ; also incentives such as tax credits, grants, loans and other financial incentives for LFG projects differ across states.
- Additional data characterizing specific landfills are necessary for a more accurate financial analysis of each technology or specific project at a specific site. Costs can vary depending on the depth area, waste composition, and annual waste in place.

Efforts to reduce landfilling (e.g., recycling, composting) can also reduce CH_4 emissions and will have an effect on the most appropriate type of project and its cost-effectiveness at a given landfill. In general, additional country specific information would be useful in determining which abatement measures would be most likely to be adopted over time.

References

CalRecycle. 2009. Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options. Obtained March 8, 201, at: http://www.calrecycle.ca.gov/climate/Events/LifeCycle/2009/default.htm.

Chartwell Information Publisher Services. 2004. *Chartwell Municipal Solid Waste Facility Directory*. Solid Waste Market Intelligence, Analysis, and Strategy Services.

Eunomia. 2008. *Development of Marginal Abatement Cost Curves for the Waste Sector.* United Kingdom: Committee on Climate Change. Defra and Environment Agency. Available at: http://www.theccc.org.uk/pdfs/Eunomia%20Waste%20MACCs%20Report%20Final.pdf

Huber-Humer, M., J. Gerber, and H. Hilber. 2008. "Biotic Systems to Mitigate Landfill Methane Emissions." *Waste Management & Research* 26: 33-46.

Intergovernmental Panel on Climate Change (IPCC). 2006. 2006 *IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual* (Volume 5-Waste). Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. As obtained on March 4, 2011.

RTI International. Municipal Solid Waste Decision Support Tool. MSW DST Documentation. Research Triangle Park, NC: RTI International. Obtained at: https://mswdst.rti.org/.

U.S. Environmental Protection Agency (USEPA). 2010. Landfill Gas Energy Cost Model. Washington, DC: USEPA, Landfill Methane Outreach Program (LMOP). Obtained at: http://www.epa.gov/lmop/publications-tools/index.html.

U.S. Environmental Protection Agency (USEPA). 2006. *Global Mitigation of Non-CO_2 Greenhouse Gases*. Washington, DC: USEPA. EPA 430-R-06-005. Obtained on February 18, 2011, at: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA).2008. *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills*. EPA/600/R-08-116. Washington, DC: USEPA. Available at: http://www.epa.gov/ttn/chief/ap42/ch02/draft/db02s04.pdf.

U.S. Environmental Protection Agency (USEPA). 2009. *Municipal Solid Waste in the United States: 2009 Facts and Figures*. Washington, DC: USEPA, Office of Solid Waste and Emergency Response. Obtained on March 3, 2011, at: http://www.epa.gov/osw/nonhaz/municipal/msw99.htm.

U.S. Environmental Protection Agency (USEPA). September 2010. *Project Development Handbook*. Chapter 3. Project Technology Options. Landfill Methane Outreach Program. Available at: http://www.epa.gov/lmop/publications-tools/#one

U.S. Environmental Protection Agency (USEPA). 2011. *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2011*. Washington, DC: USEPA, Office of Solid Waste and Emergency Response. Obtained on March 7, 2011, at: http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

U.S. Geologic Survey (USGS). 2012. *Mineral Commodities Summary: Iron & Steel Scrap.* Available at: http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_scrap/.

Unnikrishnan, S., and A. Singh. 2010. "Energy Recovery in Solid Waste Management through CDM in India and Other Countries." *Resources, Conservation and Recycling* 54(10): 630-640. doi:16/j.resconrec.2009.11.003

Van Haaren, R., N. Themelis, and N. Goldstein. 2010. "17th Annual BioCycle Nationwide Survey: The State of Garbage in America." *BioCycle* October.

Weitz, K. 2011. "Updated Research on Methane Oxidation in Landfills." Technical memorandum providing an update to previous (March 2006) research on methane oxidation rates in landfills. Prepared for Rachel Schmeltz, EPA, Climate Change Division. January.

World Bank Group. 2010. *2009—World Development Indicators: Table 2.1 Population Dynamics*. Obtained on March 8, 2011, at: http://data.worldbank.org/data-catalog/world-development-indicators.

Zhu, D., P.U. Asnani, C. Zurbrügg, S. Anapolsky and S. Mani. 2007. "Improving Municipal Solid Waste Management in India." Washington DC: The World Bank.

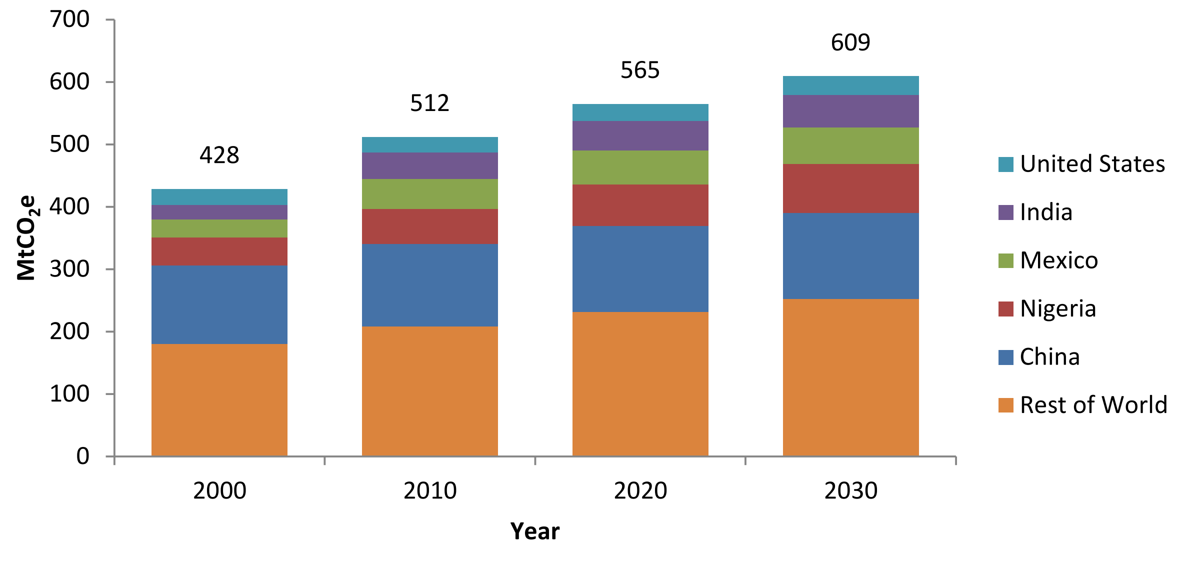
III.2. Wastewater

III.2.1 Sector Summary

Domestic and industrial wastewater treatment activities can result in deliberate venting and fugitive emissions of methane (CH_4). In addition, domestic wastewater is also a source of nitrous oxide (N_2O) emissions. CH_4 is produced when the organic material present in the wastewater flows decomposes under anaerobic conditions. Although most developed countries rely on centralized aerobic wastewater treatment systems, which limit the level of CH_4 generated, less developed countries often rely on a broader suite of wastewater treatment technologies with a significant proportion of wastewater flows handled by anaerobic systems such as septic tanks, latrines, open sewers, and lagoons (USEPA, 2012a).

Worldwide CH_4 from wastewater accounted for more than 500 $MtCO_2e$ in 2010. Wastewater is the fifth largest source of anthropogenic CH_4 emissions, contributing approximately 4% of total global CH_4 emissions in 2010. China, Nigeria, Mexico, India, and the United States, combined account for 60% of the world's CH_4 emissions from wastewater (see Figure 2-1). Global CH_4 emissions from wastewater are expected to grow by approximately 19% between 2010 and 2030.

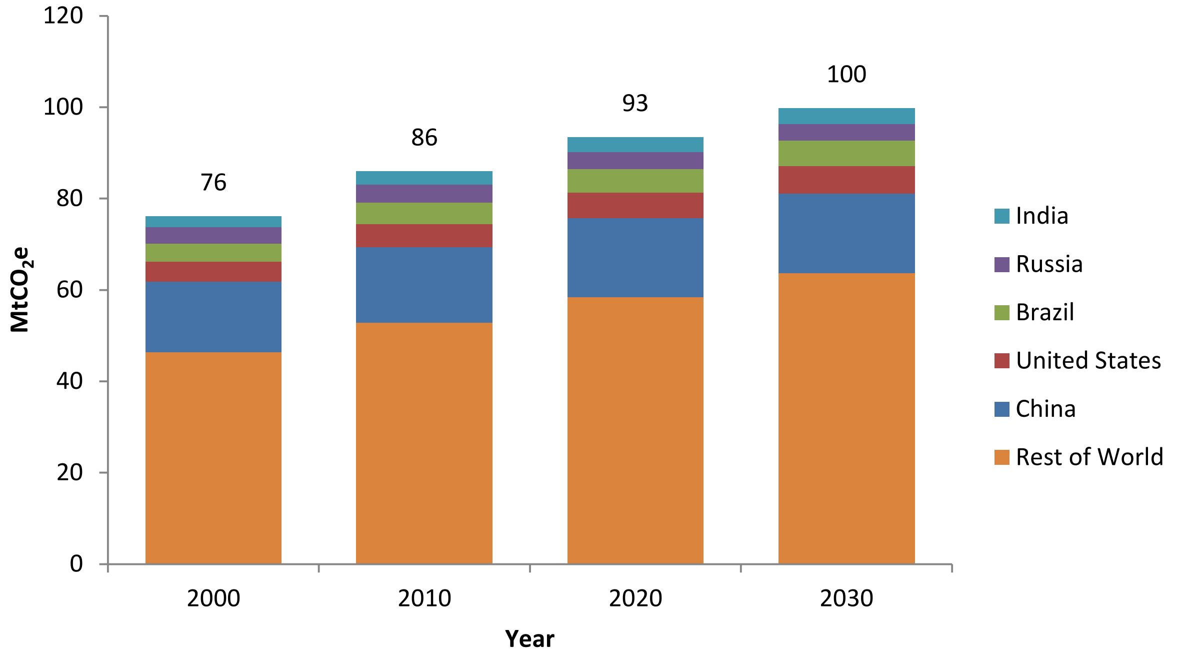
Figure 2-1: CH_4 Emissions from Wastewater: 2000–2030



Source: U.S. Environmental Protection Agency (USEPA). 2012a.

N_2O emissions from human sewage are a second significant source of GHG emissions within the wastewater sector, contributing an additional 2% of global N_2O emissions in 2010. Figure 2-2 illustrates the growth in N_2O emissions out to 2030 for the wastewater sector. China, the United States, Brazil, Russia, and India are projected to be the five largest emitters of N_2O in 2030, representing 36% of total N_2O emissions in the wastewater sector. Growth in N_2O emissions between 2010 and 2030 is expected to be 16%, slightly lower than the projected growth in CH_4 emissions over the same time period.

Figure 2-2: N_2O Emissions from Domestic Wastewater: 2000–2030



Source: U.S. Environmental Protection Agency (USEPA). 2012a.

Global abatement potential[1] of CH_4 in wastewater treatment is 138 and 218 $MtCO_2e$ in 2020 and 2030, respectively.[2] These corresponding sectoral MAC curves are shown in Figure 2-3. As the marginal abatement cost (MAC) curves show, high-cost mitigation measures in the wastewater treatment sector constrain the level of abatement achievable at lower carbon prices (less than \$30 tCO_2e^{-1}) to less than 5% of CH_4 emissions in 2030. Maximum abatement potential (218 $MtCO_2e$) is 36% of total CH_4 emissions in the wastewater sector in 2030.

The following section provides a brief explanation of sector activity, how CH_4 and N_2O emissions are generated, and projected emissions from wastewater from 2010 to 2030. Subsequent sections characterize the abatement measures available to the wastewater sector and present the costs of their implementation and operation. The chapter concludes with a discussion of the MAC analysis approach unique to this sector and presents the regional MAC results.

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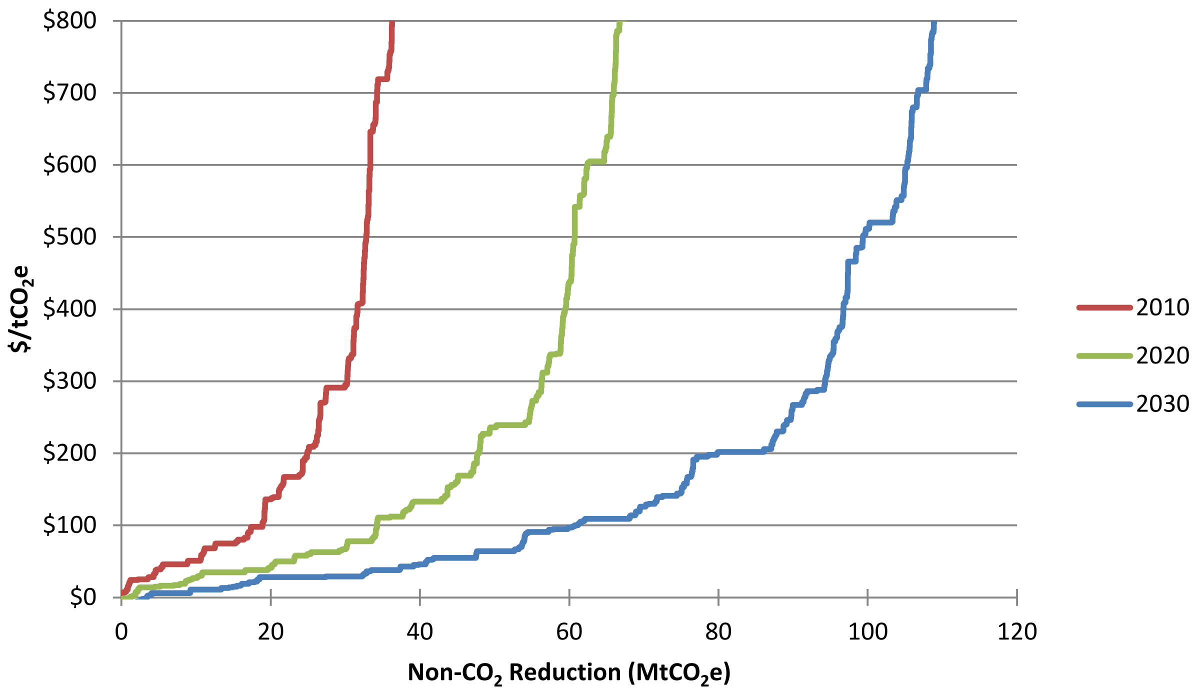
[1] This analysis only assesses abatement measures to reduce CH_4 emissions. Mitigation potentials reported in this chapter do not consider potential reductions in N_2O emissions, because of limited information on abatement measure costs.

[2] Vertical axis is scaled to limited range of prices between \$0 and \$800/tCO_2e. This scale was chosen because it shows sufficient detail in the MAC curves at lower break-even prices. Only 45% of the total abatement is visible in the figure simply due to the price limits chosen for the vertical axis when reporting the data.

Figure 2-3: Global MAC for Wastewater: 2010, 2020, and 2030



III.2.2 GHG Emissions from Wastewater

This section discusses how CH_4 and N_2O emissions are produced in wastewater treatment and disposal activities and the current projections of baseline emissions between 2010 and 2030.

III.2.2.1 CH_4 Emissions from Domestic and Industrial Wastewater

CH_4 is emitted during the handling and treatment of domestic and industrial wastewater. Wastewater CH_4 emissions are produced through the anaerobic decomposition of organic material present in the wastewater. Three key factors that determine the CH_4 generation potential are the quantity of degradable organic material present in the wastewater, the temperature, and the type of treatment system used (Intergovernmental Panel on Climate Change [IPCC], 2006). The organic content of wastewater is typically expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD) (IPCC, 2006; USEPA, 2012a). CH_4 generation is positively related to temperature so that higher temperatures result in a great amount of CH_4 produced. The third key factor that determines CH_4 generation is the type of treatment system used and more specifically the amount of decomposition occurring under anaerobic conditions which is positively related the quantity of CH_4 generated.

Types of centralized systems that can result in CH_4 emissions include 1) aerobic systems that are either improperly operated or designed to have periods of anaerobic activity and 2) anaerobic lagoons (USEPA, 2012b). Most developed countries currently use centralized aerobic wastewater treatment facilities with closed anaerobic sludge digester systems to process municipal and industrial wastewater, minimizing CH_4 emissions.

The IPCC guidelines for national greenhouse gas reporting identifies five major industrial wastewater sources for CH_4 emissions, which include pulp and paper manufacturing, meat and poultry processing (slaughterhouses), alcohol/beer and starch production, organic chemicals production, and other drink and food processing (e.g., dairy products, vegetable oil, fruits and vegetables, canneries, juice making) (IPCC, 2006). The significance of CH_4 emissions from the various industrial sources will depend on the concentration of degradable organics present in the wastewater flow, volume of wastewater generated, the quantity of wastewater treated in anaerobic treatment systems (e.g., anaerobic lagoons).

III.2.2.2 N_2O Emissions from Domestic Wastewater—Human Sewage

N_2O is produced during both the nitrification and denitrification of urea, ammonia, and proteins. These waste materials are converted to nitrate (NO_3) via nitrification, an aerobic process converting ammonia-nitrogen to nitrate. Denitrification occurs under anoxic conditions (without free oxygen) and involves the biological conversion of nitrate into dinitrogen gas (N_2). N_2O can be an intermediate product of both processes but is more often associated with denitrification (Sheehle and Doorn, 2002).

III.2.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions for the wastewater sector.[3] Historical emissions are characterized as those emissions released between 1990 and 2010. Projected emissions estimates cover the 20-year period starting in 2010 and ending in 2030.

Historical Emissions Estimates

Between 1990 and 2005, CH_4 and N_2O emissions from wastewater increased by 20% from a combined total of 421 $MtCO_2e$ in 1990 to 505 $MtCO_2e$ in 2005. The primary driver of both CH_4 and N_2O emissions associated with wastewater is population growth. Country-level CH_4 emissions are particularly sensitive to population growth in countries that rely heavily on anaerobic treatment systems such as septic tanks, latrines, open sewers, and lagoons for wastewater treatment (USEPA, 2012a).

The share each countries total emissions that is attributed to domestic versus industrial wastewater sources is determined by the level of industrial activity and types of domestic wastewater treatment systems employed. In developing countries, domestic wastewater sources account for the majority if not all of CH_4 emissions from wastewater. In countries with industrial wastewater sources, the contribution of industrial wastewater emissions will depend on the level of production and the commodity produced (e.g. paper, sugar, alcoholic beverages, and processed meat/poultry/fish). Based on the UNFCCC's national reporting inventory database of GHG emissions, only a small number of developed countries have historically reported CH_4 emission from Industrial sources. For these 24 countries reporting industrial and domestic CH_4 emissions the share of emissions reported for industrial wastewater ranged from less than 2% to nearly 70% of total CH_4 emissions from all wastewater sources. Section III.2.4 discusses these distributions of emissions to domestic and industrial sources in more detail.

Projected Emissions Estimates

Worldwide CH_4 emissions are projected to increase by approximately 19% (97 $MtCO_2e$) between 2010 and 2030. N_2O emissions are projected to increase by a similar proportion, up 16% (14 $MtCO_2e$) over the same time period. Tables 2-1 and 2-2 present the CH_4 and N_2O emissions projections for the wastewater sector.

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[3] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's *Global Emissions Projection Report* available at: http://www.epa.gov\climatechange\economics\international.html.

Table 2-1: Projected CH_4 Baseline Emissions from Wastewater: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	132	135	137	138	138	0.2%
Nigeria	56	62	67	73	78	1.7%
Mexico	48	51	54	56	58	0.9%
India	42	45	47	50	52	1.1%
United States	25	26	27	29	30	0.9%
Rest of Regions						
Africa	27	29	32	35	38	1.9%
Central & South America	47	50	53	56	59	1.1%
Middle East	22	23	25	26	28	1.2%
Europe	19	19	20	20	20	0.2%
Eurasia	26	25	25	24	23	−0.5%
Asia	68	72	76	81	84	1.1%
North America	0	0	0	0	0	0.7%
World Total	**512**	**539**	**565**	**588**	**609**	**0.9%**

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA). 2012a.

Table 2-2: Projected N_2O Baseline Emissions from Human: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	17	17	17	17	17	0.2%
United States	5	5	6	6	6	0.9%
Brazil	5	5	5	5	6	0.9%
Russia	4	4	4	4	4	1.1%
India	3	3	3	3	4	−0.6%
Rest of Region						
Africa	11	13	14	15	17	1.8%
Asia	5	5	6	6	6	1.0%
Central & South America	4	5	5	5	6	1.0%
Eurasia	14	14	14	14	14	0.1%
Europe	3	3	3	3	3	0.0%
Middle East	12	13	14	14	15	1.3%
North America	3	3	3	3	3	0.9%
World Total	**86**	**90**	**93**	**97**	**100**	**0.7%**

Source: U.S. Environmental Protection Agency (USEPA). 2012a.

As shown in Table 2-1, Africa and the Middle East are two regions projected to experience significant growth in CH_4 emissions over the next 20 years, increasing by 50% and 33%, respectively. CH_4 emissions growth in Asia and the Central and South American regions is also expected to be significant, growing by 25% over the same time period.

N_2O emissions are expected to grow by similar proportions across all regions with the exception of Eurasia, where emissions are expected to remain relatively unchanged over the next 20 years. The primary driver of this trend is Russia's 11% drop in N_2O emissions between 2010 and 2030. Despite this decline, Russia still ranks as one of the top five emitters in 2030.

III.2.3 Abatement Measures and Engineering Cost Analysis

This section characterizes the abatement measures considered for the wastewater sector. This analysis focused on domestic wastewater treatment and implementation of abatement measures aimed at reducing CH_4 emissions, which can be mitigated through investment in infrastructure and/or equipment. Conversely, there are no proven and reliable technologies for mitigation of N_2O emissions. Mitigation steps to limit N_2O emissions from wastewater treatment are operational, and include careful control of dissolved oxygen levels during treatment, controlling the biological waste load-to-nitrogen ratio, and limiting operating system upsets. These measures require technical expertise and experience rather than an engineered solution, thus they fall outside the scope of an engineered cost analysis.

It is important to couch the discussion of greenhouse abatement measures for municipal wastewater in the appropriate context. In practice, changes to wastewater management strategies in developing countries are unlikely to be driven by the mitigation of greenhouse gases. Factors such as economic resources, population density, government, and technical capabilities are all important in determining both the current state and the potential for improvement to a country's wastewater sanitation services. Figure 2-4 is an illustration of the sanitation ladder, which relates the level of available wastewater sanitation to the population and cost for treatment. The transition from a latrine to a sewer/wastewater treatment plant (WWTP)/anaerobic digester can increase the operation and maintenance wastewater treatment cost per person by a factor 20 (Guchte and Vandeweerd, 2004). This does not account for the capital cost that would be required in such large scale projects.

The reader should bear in mind throughout the analysis that the wastewater sanitation technology is likely to be fixed by these external factors, and improvements in technology will be driven by the population's desire/capacity for improved sanitation and hygiene, with any improvements to greenhouse gas emissions a secondary result of the change. Thus, although abatement measures are presented in this chapter, they should not be considered to be a viable control measure that could be implemented for the sole purpose of reducing a country's GHG emissions, but rather a byproduct of a country's position on the sanitation ladder.

This analysis considers abatement measures that may be applied to one of five existing wastewater treatment systems currently being utilized in a given country. Scenarios 1 and 2 correspond to the upper half of the sanitation ladder, while scenarios 3 through 5 correspond to the lower half the sanitation ladder. The five baseline scenarios for the existing status quo are presented in Figure 2-5. In actuality, there are many more than five baseline technology scenarios that may be utilized throughout the world, within a country, or even within a municipality. For example, a population may utilize aerobic or anaerobic ditches for centralized treatment of wastewater, which could be viewed as an intermediate option between scenarios 1 and 2 in Figure 2-5. These baseline scenarios are not meant to be an exhaustive list of the actual existing treatment technologies employed worldwide, but rather an attempt

Figure 2-4: Sanitation Ladder for Improvements to Wastewater Treatment

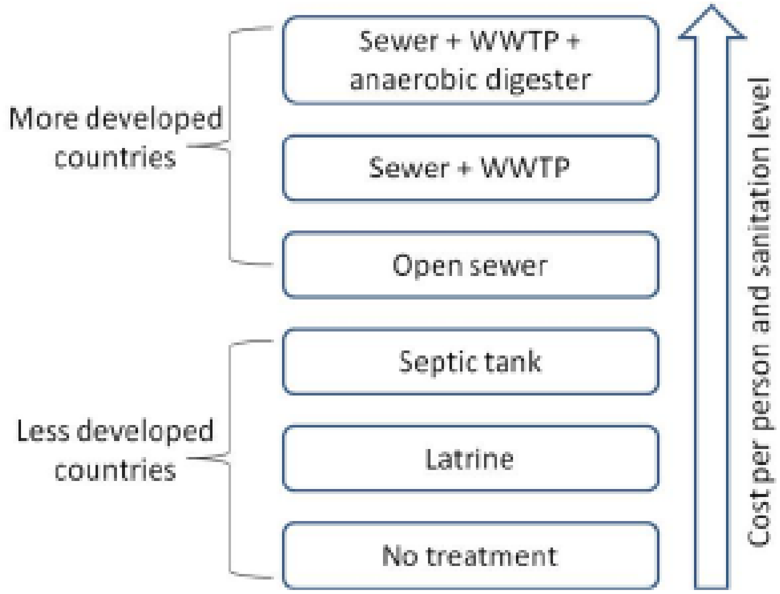
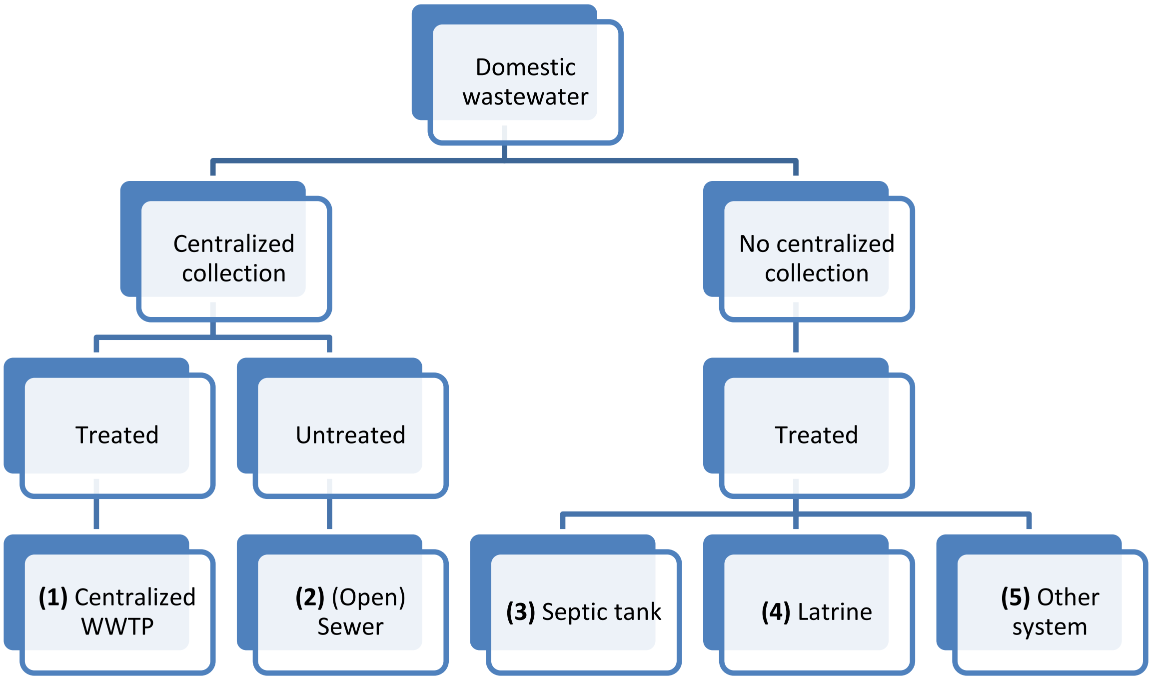


Figure 2-5: Five Existing Scenarios Evaluated for Given Wastewater Discharge Pathways Based on Technology Level, Treatment Alternative, and Collection Method



to broadly categorize and quantify technologies that represent the major classes of treatment technologies employed throughout the world.

Discharge pathways 1 and 2 (in Figure 2-5) assume the existence of a collection system for all wastewater generated and are grouped according to the final disposal/treatment approach. Pathways 3, 4, and 5 are the scenarios for which no existing centralized treatment exists and the waste is treated on site with latrines or septic tanks. For each of the five pathways and corresponding treatment systems, a mitigation approach is evaluated for CH_4 reduction. The analysis considers three abatement measures that include both mitigation technologies as well as complete shifts in wastewater management, that is, a jump up the sanitation ladder.

It is important to note the distinction between the two types of abatement measures. Mitigation technologies represent add-on technologies that can be applied to existing wastewater treatment systems (such as an anaerobic digester with cogeneration) intended to capture and destroy the CH_4 generated at the facility. The second type of abatement measure represents a shift away from an existing anaerobic wastewater treatment approach to an aerobic system which in turn will reduce the volume of CH_4 generated during the treatment process. This shift in wastewater treatment approaches will require the construction of a new facility that fundamentally changes the existing wastewater management approach. This approach usually requires construction of new infrastructure and, therefore, will require significant capital investment. As demonstrated in the cost analysis, the construction and operation and maintenance cost per person is dependent on the population density of the region. For a collection system, more rural areas require the more material (per person) to be used to build a system to collect and transport the waste.

III.2.3.1 Overview of Abatement Measures

This section discusses the abatement measures considered for this analysis. Each technology is briefly characterized and followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis. Table 2-3 compares the three abatement alternatives for an example population of 400,000 people, population density of 3,000/km², and wastewater generation rate of 340 L/person/day.

Table 2-3: Abatement Measures for the Wastewater Sector

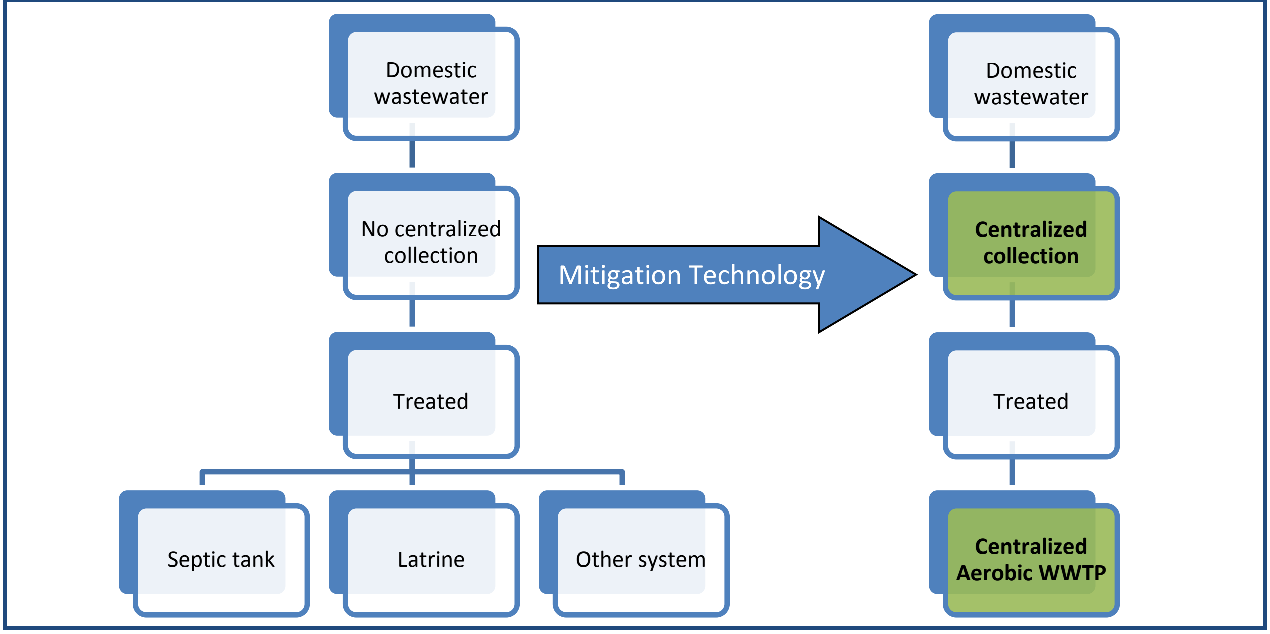
Abatement Option	Total Installed Capital Cost (2010 106 USD)	Annual O&M Cost (2010 106 USD)	Time Horizon (Years)	Technical Efficiency
Anaerobic biomass digester with CH_4 collection and cogen.	21.1	5.0	20	60–80%
Aerobic wastewater treatment plant (WWTP)	97.2	4.7	20	60–80%
Centralized wastewater collection (+ aerobic WWTP)	55.9 (153.1)	1.6 (6.3)	50	60–80%

For this analysis, abatement measures are assigned based by on the existing wastewater treatment system pathway in place. For example, a population considering the addition of an anaerobic biomass digester will already have an existing collection system and aerobic WWTP in place. There is no technology selection in the current analysis because we have identified one abatement measure for each type of treatment system. The following subsections characterize each of the three abatement measures and the assumptions regarding applicability and costs. In reality, feasible mitigation measures will vary due to the wide range of wastewater disposal options currently employed in each country and the external factors that govern a country's ability to transition from one technology to another. In addition, as discuss above regarding the baseline scenarios, there are dozens of wastewater technology options available to a population; this discussion highlights three major categories that represent shifts in water management or add-on technology.

III.2.3.2 CH_4 Mitigation Technology for Existing Decentralized Treatment

This section characterizes the reduction in CH_4 emissions by adding a collection system and centralized treatment facility in developing countries where the current practice is decentralized wastewater treatment. As shown in Figure 2-6, this approach necessitates two large-scale capital investments: the construction of a sewerage system for centralized collection and the construction of an anaerobic WWTP.

Figure 2-6: Mitigation Technology Approach for Developing Countries with Decentralized Treatment



Wastewater Collection System—New Construction

For areas of the developing world without centralized wastewater treatment, latrines and/or septic tanks are typically used to dispose of domestic wastewater. In both of these cases, the organic matter in the wastewater will undergo anaerobic degradation to produce CH_4. The construction and implementation of a collection system and subsequent treatment at a centralized facility would significantly reduce CH_4 formation because transporting wastewater through sewers promotes aerobic conditions and reduces the fraction of organic content that undergoes anaerobic digestion.

The design and size of a wastewater collection system depend on the population served, the service area size, and water use characteristics of the population. Wastewater collection systems link all household and commercial discharges through underground piping, conveying the water to either a centralized treatment facility or directly to an outfall point where it is released into the environment. Pipelines can vary from 6 inches in diameter to concrete-lined tunnels up to 30 feet in diameter. Collection systems are built with a gradient so gravity can facilitate the water flow; where there are large distances that must be covered, periodic pump stations (also called lift stations) are sometimes used to pump the sewage to a higher elevation and again allow gravity to transport the sewage. Sewage pumps are typically centrifugal pumps with open impellers, designed to have a wide opening to prevent the raw sewage from clogging the pump. This scenario evaluates the impact of installing a sewer collection system without a centralized treatment facility.

- **Capital Cost:** The cost estimation model Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR) (Finney and Gearheart, 2004) was used to determine the capital cost of the sewer construction. The model is used by engineers, planners, decision makers, and financiers to estimate the costs of making improvements to wastewater treatment systems while minimizing impacts to water resources. The capital cost curve for wastewater collection systems is based on the population density: Capital Cost ($MM/km^2) = $360.54 \times D_p^{-0.844}$, where D_p is population density in (persons/km^2).
- **Annual Operation and Maintenance (O&M) Cost:** Annual O&M costs for collection systems were scaled from the capital cost and assumed to be a factor of 0.028 × initial capital cost, which for this case gives the following cost curve, based on population density: O&M Cost ($MM/km^2) = $10.095 \times D_p^{-0.844}$.
- **Annual Benefits:** No benefits are associated with this option.
- **Applicability:** This option applies to all scenarios having no existing centralized collection system.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year, due to an assumed improvement in technical efficiency.
- **Technical Lifetime:** 50 years

Aerobic WWTP—New Construction

Contaminants in wastewater are removed using a variety of physical, chemical, and biological methods. A WWTP typically comprises many unit operations from each of these broad categories. Wastewater treatment technologies are also divided into stages of treatment, each of which comprises one or more individual treatment processes. A brief summary of each of these classifications is as follows:

- **Pretreatment:** This stage involves the removal of wastewater constituents. These constituents can include rags, sticks, floatables, grit, and grease that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems. Screening methods are employed here, suing bars, rods, grates, or wire meshes.
- **Primary treatment:** This stage focuses on the removal of a portion of the total suspended solids (TSS) and organic matter from the wastewater. Primary treatment is a physical unit process in which the sewage flows into large tanks, known as primary clarifiers or primary settling tanks. A settling tank is constructed of concrete and designed so that the residence time of the wastewater is such that the flow slows down enough so that readily settleable particles are collected at the bottom of the tank.
- **Secondary treatment:** This stage focuses on the removal of biodegradable organic matter (in solution or suspension) and TSS by aerobic or anaerobic biological treatment. Disinfection is also typically included in the definition of conventional secondary treatment. Secondary treatment is a biological process that cultivates and uses a consortium of microorganisms to degrade the organic wastes and reduce nutrient levels in wastewater. Secondary treatment can either be aerobic (with oxygen) or anaerobic (without oxygen). By far, the most common approach used in WWTPs is the activated sludge process. This process is an aerobic suspended-growth system

containing a biomass that is maintained with oxygen and is capable of stabilizing organic matter found in wastewater. During the activated sludge process, the effluent flows into a concrete tank where air or oxygen is bubbled through the wastewater to encourage microbial degradation of the organic material. The treated effluent flows to a secondary settling tank, where it is separated from the biomass. Most of the biomass collected at the bottom of the settling tank is removed for further dewatering and stabilization before final disposal. A small fraction of the biomass is recycled back into the bioreactor to maintain the population. It is important to monitor proper control of oxygen levels, pH, and the amount of sludge recycled back into the reactor to ensure that proper treatment levels of the wastewater are maintained.

- **Tertiary treatment:** This stage involves the removal of residual suspended solids (after secondary treatment), usually by granular medium filtration or microscreens. Disinfection is also typically a part of tertiary treatment. Nutrient removal is often included in this stage.

The cost breakdown for this mitigation approach is as follows:

- **Capital Cost:** Capital costs were estimated using EPA cost curves detailing the construction costs of publicly owned wastewater treatment facilities (USEPA 1980). The costs curves in this report are based on actual winning bids for treatment plans, which include detailed equipment and materials requirements, including labor, amortization, land, concrete, pumps, pipes, power, haulage, chemicals, and design fees. All cost curves were updated to year 2010 dollars. The cost curve is based on the flow rate of the WWTP: Capital Cost (\$MM) = $0.0174 \times Q^{0.73}$, where Q is the flow rate in m^3/day.
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs of an aerobic WWTP are due to electricity used to provide aeration and operation equipment, labor to operate the plant, chemicals, and equipment replacement. EPA cost curves (updated to 2010 dollars) provides the following cost curve for an aerobic WWTP, based on the flow rate: $0.0002 \times Q^{0.8517}$.
- **Annual Benefits:** None.
- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.

III.2.3.3 CH_4 Mitigation Technology for Existing Collection System without Treatment

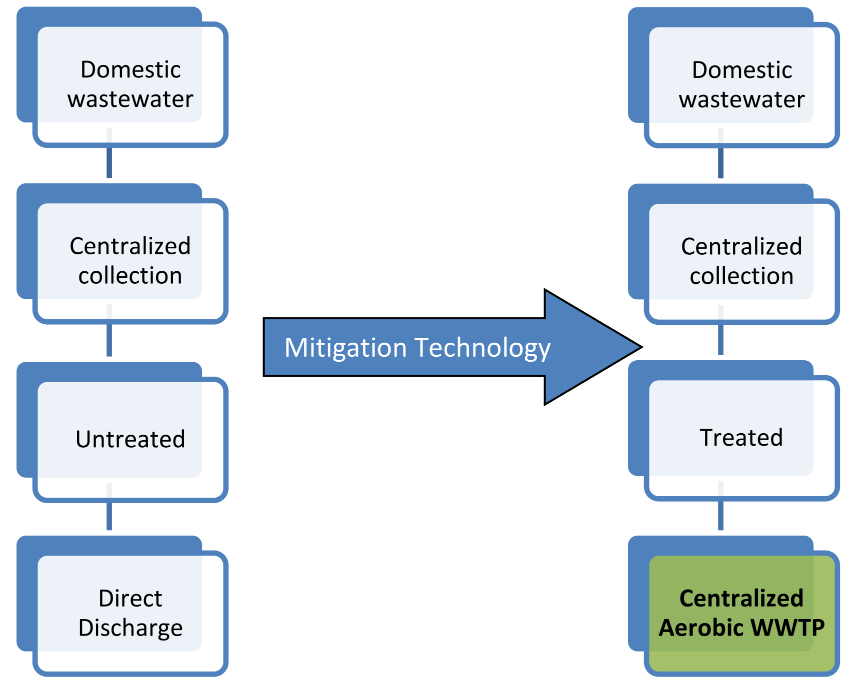
This section characterizes the reduction in CH_4 emissions for the existing condition of a centralized collection system without a treatment facility**.** Figure 2-7 illustrates the step change in technical capability, which in this case necessitates the construction of a new anaerobic WWTP.

As noted above, contaminants in wastewater are removed via a variety of physical, chemical, and biological methods. An anaerobic WWTP typically comprises many unit operations divided into stages of treatment: pretreatment, primary treatment, secondary treatment, and tertiary treatment.

The cost breakdown for this mitigation approach is identical to that above and is as follows:

- **Capital Cost:** Capital costs were estimated using EPA cost curves detailing the construction costs of publicly owned wastewater treatment facilities. The cost curve is based on the flow rate of the WWTP: Capital Cost (\$MM) = $0.0174 \times Q^{0.73}$, where Q is the flow rate in m^3/day.

Figure 2-7: Mitigation Technology Approach for Developing Countries with Decentralized Treatment

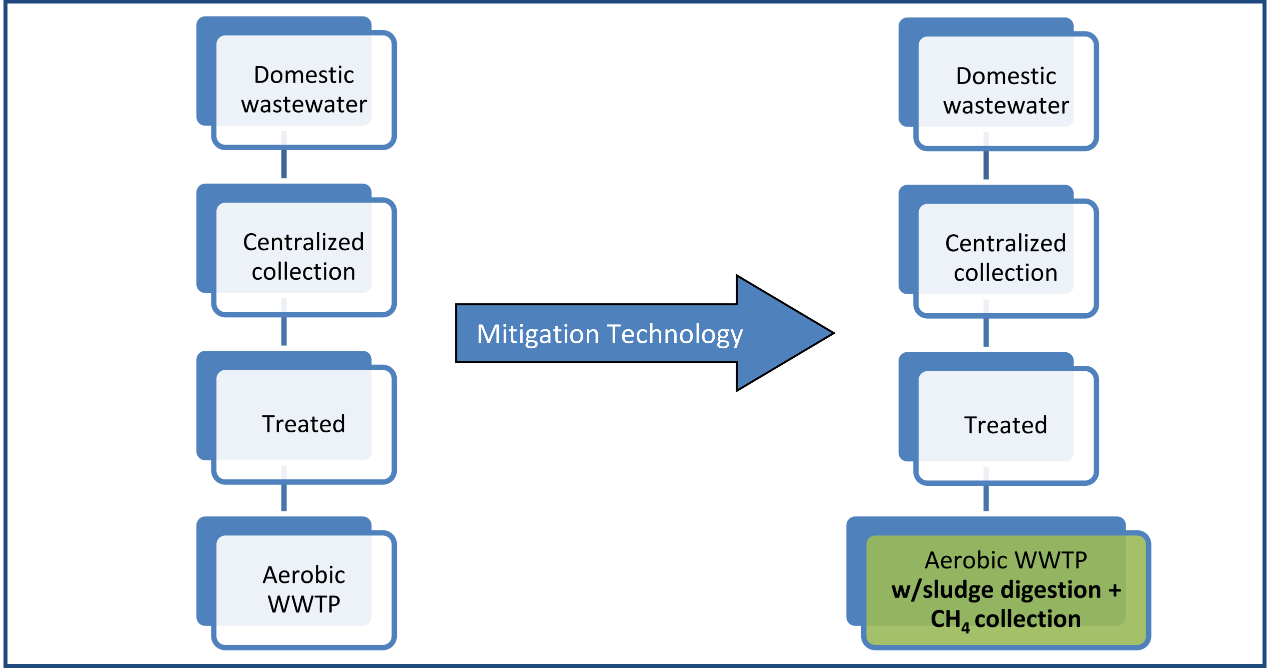


- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs of an aerobic WWTP are due to electricity used to provide aeration and operation equipment, labor to operate the plant, chemicals, and equipment replacement. Capdetworks v2.5 was used to estimate O&M costs. Capdetworks is a planning level tool that enables the user to evaluate the costs associated with individual treatment units or entire systems. The costs are based on detailed equipment and materials database that utilizes published cost indices, including labor, amortization, and energy requirements. Capdetworks provides the following cost curve for an aerobic WWTP, based on the flow rate: O&M cost ($MM) = $0.0002 \times Q^{0.8517}$.
- **Annual Benefits:** None.
- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.

III.2.3.4 CH_4 Mitigation Technology for Existing Centralized Aerobic WWTPs

This section characterizes the reduction in CH_4 emissions from adding an activated sludge digester for CH_4 collection and energy generation. This option is only applicable to existing centralized aerobic WWTPs primarily found in developed countries (Figure 2-8).

Figure 2-8: Mitigation Technology Approach for Countries with Existing Centralized WWTPs



Anaerobic Biomass Digester with CH_4 Collection

The top of the technology ladder evaluated assumes an existing centralized WWTP is used to treat all wastewater generated in the region. The significant quantity of biomass generated during the decomposition of the sewage is a major operational component of WWTP operation. Typical approaches to sludge handling include dewatering to reduce the overall volume and further water reduction in open-air drying beds. The sludge is rich in organic matter and has the potential to produce high amounts of CH_4 during degradation. Anaerobic digestion is an additional sludge-handling step that can be employed to further reduce the sludge volume; it is a process that involves the decomposition of this organic material in an oxygen-free environment to produce and collect CH_4. Anaerobic digesters are large covered tanks that are heated to optimize the methane-generating process. The tanks typically employ a mixing mechanism to ensure uniform conditions throughout the tank and are designed with headspace to collect the gas generated, which is typically a mix of 60 to 70% CH_4 and the 30 to 40% CO_2, along with trace gases. The remaining solid material is nutrient rich and is a suitable fertilizer for land application. The heat from the flared gas can be used to heat the digester, lowering the overall energy requirements of the system. Alternatively, the gas can be used to produce electricity with a turbine.

- **Capital Cost:** Costs were derived from EPA process cost curves for new construction of an anaerobic digester. The capital cost covers the construction of the tank with heater and cover and includes concrete, all equipment, process piping and steel required for digester construction. Costs were derived from CapdetWorks. The cost curve is based on the flow rate of the WWTP: Capital Cost ($MM) = $0.0004 \times Q^{0.92}$, where Q is the flow rate in m^3/day.
- **Annual Operation and Maintenance (O&M) Cost:** Typical annual O&M costs for collection systems are based on CapdetWorks. CapdetWorks provides the following cost curve for aerobic WWTP, based on the flow rate: O&M cost ($MM) = $0.00042 \times Q^{0.7939}$.

- **Annual Benefits:** Stabilized sludge can be land applied as fertilizer. The cogeneration option provides electricity. Flared gas can be used elsewhere at the plant to reduce overall energy requirements.
- **Applicability:** This option applies to all existing WWTP types.
- **Technical Efficiency:** This analysis assumes an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years

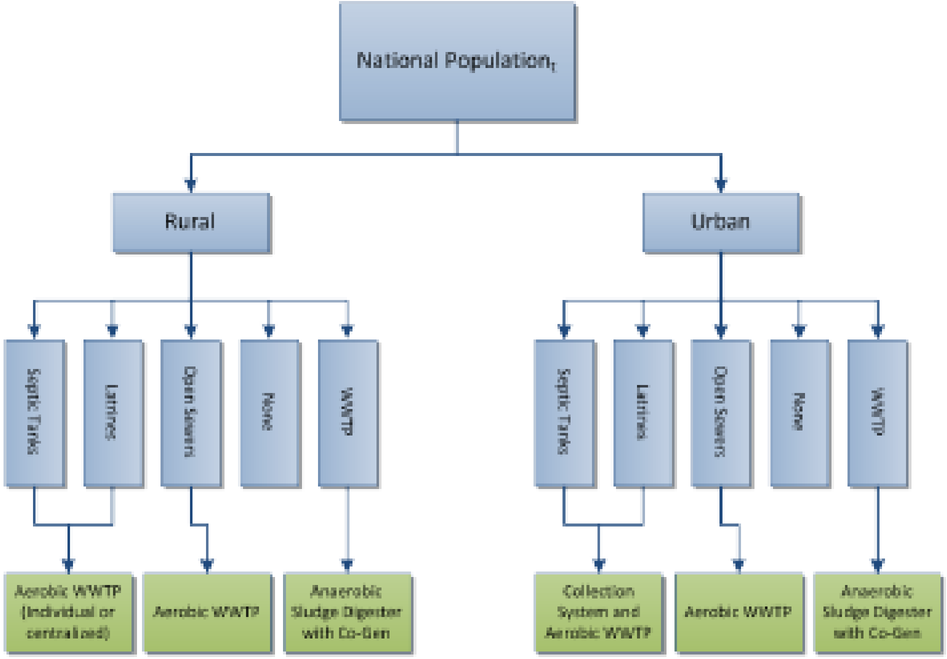
III.2.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the international assessment of CH_4 abatement measures for wastewater treatment systems.

III.2.4.1 Methodological Approach

The MAC analysis is based on project costs developed for a set of model facilities based on the technical and economic parameters discussed in Section III.2.3. Similar to the steps taken in other sectors, we developed an inventory of facilities that are representative of existing facilities. Next, we applied the abatement costs reported above to calculate the break-even prices for each option and wastewater treatment scenario. Finally, the model estimates the mitigation potential based on the country-specific share of emissions attributed to each wastewater treatment scenario. Figure 2-9 shows the organization of the domestic wastewater MAC model. The country-specific distributions are based on analysis conducted by USEPA (2012a).

Figure 2-9: Domestic Wastewater MAC Analysis Flow Chart

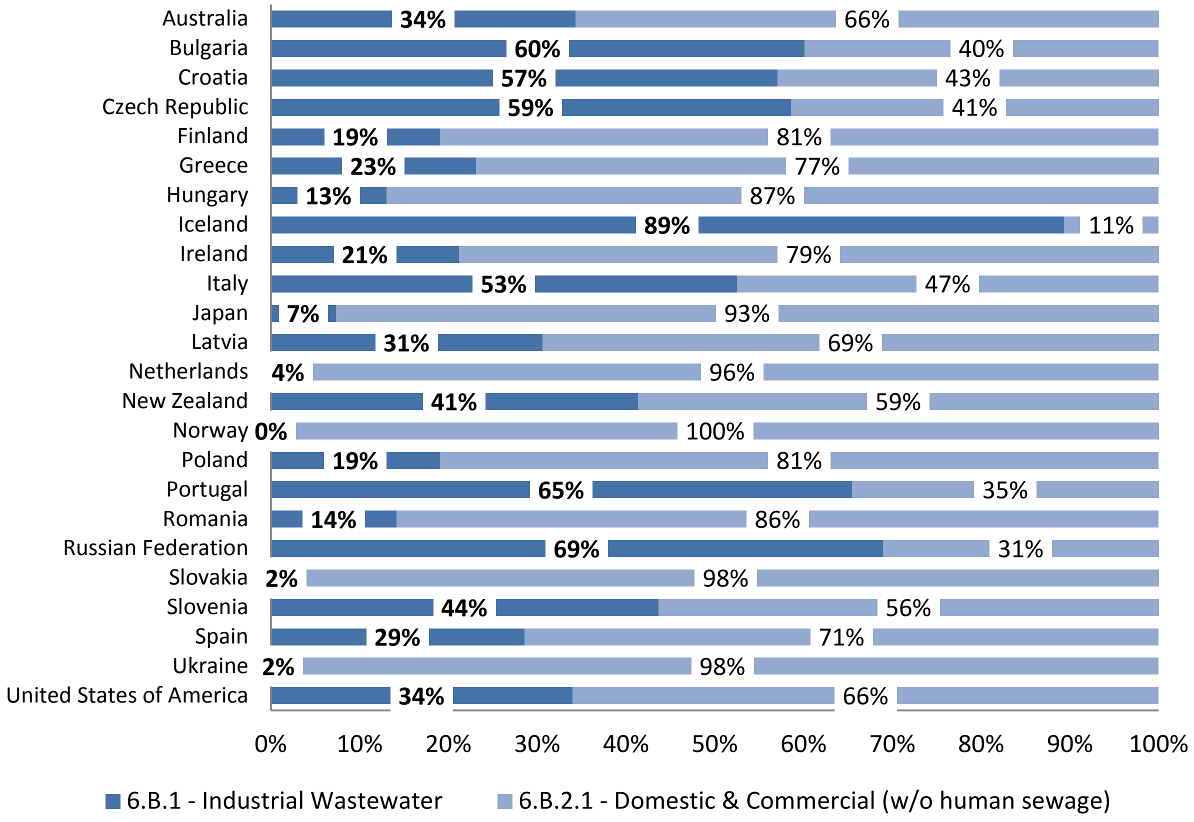


Assessment of Sectoral Trends

The first step in the analysis is to assess the level of baseline emissions attributable to domestic versus industrial wastewater sources. The analysis allocates, when information is available, a percentage of annual emissions to domestic wastewater treatment. For each country, the remaining share of emissions is allocated to industrial wastewater treatment.

Shares allocated to each source (domestic/industrial) were based on historical emissions data obtained from the United Nations Framework Convention on Climate Change's (UNFCCC's) GHG emissions reporting database. Data were limited to 24 Annex I countries accounting for 15% of emissions in 2010. For these 24 countries, we calculated a 5-year average share of CH_4 emissions attributable to domestic sources based on emissions reported between 2002 and 2007. For all other countries, because of a lack of data, we assumed emissions projections are wholly attributable to domestic wastewater treatment systems to be consistent with USEPA (2012a) projections methodology. Figure 2-10 presents the average share of emissions attributed to domestic and industrial sources by country.

Figure 2-10: Share of Wastewater CH_4 Emissions to Domestic and Industrial Sources (Avg. 2002–2007)



Source: United Nations Framework Convention on Climate Change (UNFCCC). Flexible Data Queries. Online Database. Available at: http://unfccc.int/di/FlexibleQueries/Event.do?event=hideProjection.

The analysis also leverages estimated changes in wastewater disposal activity along each wastewater treatment pathway discussed earlier in this chapter. This data was obtained from previous USEPA analysis used to developed international wastewater projections. Trends in wastewater disposal activity are determined by population projections, distribution of population between rural and urban settings, population density, and wastewater flow rates per person. These parameters are used to estimate country- and technology-specific abatement project costs.

Other trends applied for this analysis include increasing the technical applicability factor and technical effectiveness factor. The technical applicability factor is assumed to increase at 1% per year between 2010 and 2030. The technical effectiveness factor increases at a similar rate, growing from 60% to 80% over the 20-year time period. These assumptions are based on expert judgment and intended to reflect increases in both the adoption of improved sanitation systems and improvements through learning best management practices for the alternative treatment systems that reduced CH_4 emissions.

Estimate Abatement Project Costs and Benefits

Project costs were estimated based on the cost functions defined in Section III.2.3. Country-specific demographic information on wastewater flow rates and population density was used to estimate the initial capital costs for each population segment. Table 2-4 provides example abatement measure cost estimates for the United States and the corresponding break-even prices associated with each option.

Table 2-4: Example Break-Even Prices for Wastewater Abatement Measures in 2030 for the United States

Abatement Option	Reduced Emissions (tCO_2e)	Installed Capital Costs ($\$/tCO_2e$)	Present Value of Annual Cost ($\$/tCO_2e$)	Present Value of After Tax Benefits ($\$/tCO_2e$)	Present Value of Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Rural						
Septic to aerobic WWTP	6,493,070	$51,771	$3,080	$179	$4,106	$5,100
Latrine to aerobic WWTP	288,581	$25,886	$1,540	$179	$2,053	$2,541
Open sewer to aerobic WWTP	—	—	—	—	—	—
Anaerobic sludge digester with co-gen	57,716	$6,929	$533	$154	$1,180	$720
Urban						
Septic to aerobic WWTP	1,082,178	$10,936	$2,251	$179	$867	$1,224
Latrine to aerobic WWTP	—	—	—	—	—	—
Open sewer to aerobic WWTP	—	—	—	—	—	—
WWTP—add-on anaerobic sludge digester with co-gen	2,056,139	$5,206	$255	$154	$886	$519

Note: Break-even price was calculated using a 10% discount rate and 40% tax rate.

III.2.4.2 MAC Analysis Results

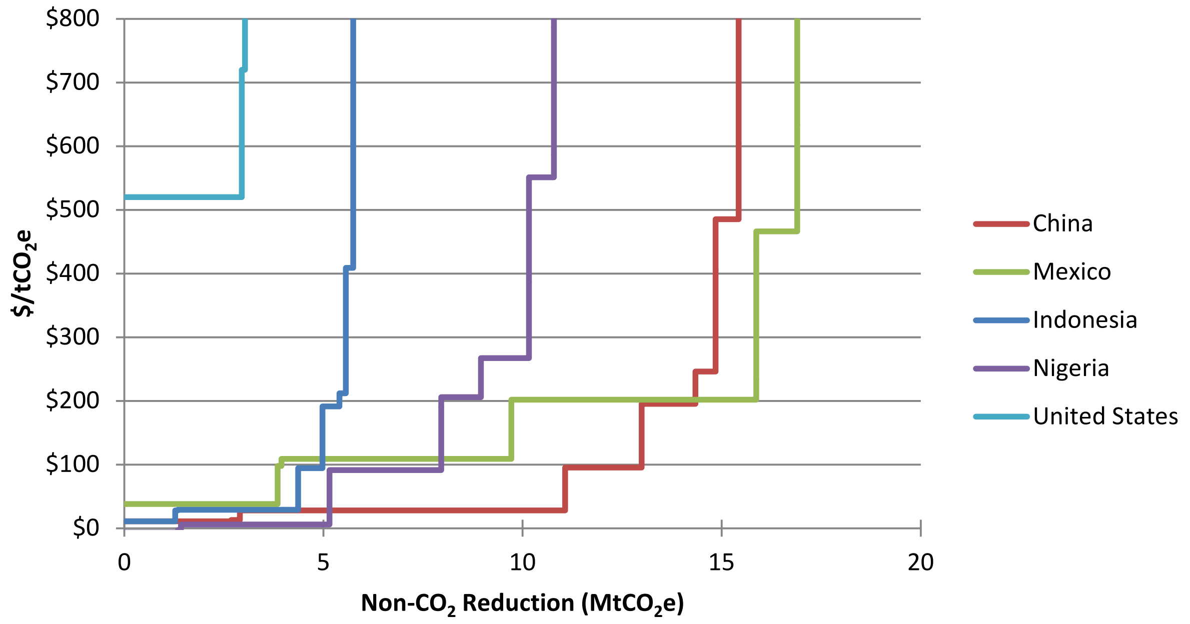
The global abatement potential of CH_4 emissions in wastewater treatment is 36% of total annual emissions by 2030. Table 2-5 and Figure 2-11 present the MAC curve results for 2030 showing a cumulative reduction potential of 218 $MtCO_2e$. The top five emitters contribute approximately 58% of total abatement potential.

Significant initial capital costs combined with no direct monetary benefits limits the abatement potential achieved at lower break-even prices. As shown in Table 2-5, less than 20% of the total abatement potential is realized at prices below $\$50/tCO_2e$ in 2030. These results do not reflect human health benefits or other positive externalities that accompany improvements in wastewater sanitation. If these additional social benefits were included, it would result in higher levels of abatement achievable at lower break-even prices.

Table 2-5: Abatement Potential by Region at Selected Break-Even Prices in 2030

Country/Region	Break-Even Price ($/tCO$_2$e) –10	–5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	—	—	—	2.9	2.9	11.1	11.1	13.0	49.7
Indonesia	—	—	—	—	—	1.3	1.3	4.4	4.4	5.0	18.8
Mexico	—	—	—	—	—	—	—	—	3.8	3.9	20.9
Nigeria	—	1.4	1.4	1.4	5.2	5.2	5.2	5.2	5.2	8.0	21.9
United States	—	—	—	—	—	—	—	—	—	—	14.3
Rest of Region											
Africa	0.2	0.5	0.7	0.9	0.9	1.4	1.5	1.6	1.8	3.2	10.8
Asia	—	0.7	0.8	0.9	2.0	2.6	2.6	3.3	5.7	6.8	21.1
Central and South America	—	—	0.0	0.0	0.0	0.0	0.0	0.2	1.3	1.8	9.9
Eurasia	—	—	—	—	—	0.1	0.1	0.3	0.7	1.0	8.9
Europe	—	—	—	—	—	—	—	—	0.0	5.5	10.9
Middle East	—	0.0	0.5	0.8	1.2	2.0	3.5	6.3	7.0	12.9	30.9
North America	—	—	—	—	—	—	—	—	—	—	0.2
World Total	**0.2**	**2.6**	**3.4**	**4.0**	**9.3**	**15.5**	**17.1**	**32.4**	**41.0**	**61.2**	**218.3**

Figure 2-11: Marginal Abatement Cost Curve for Top 5 Emitters in 2020



III.2.4.3 Uncertainties and Limitations

The 2006 version of this report did not explicitly model any abatement measures. This analysis makes an initial attempt at estimating the abatement potential that could be achieved in the wastewater sector. The previous report identified two major factors preventing the modeling of abatement in this sector. The first was data limitations on the type of treatment systems currently employed in each country. The second was the overriding economic and social factors influencing wastewater treatment practices and investment throughout the world.

The analysis presented in this chapter attempts to address the data limitations issue by estimating the quantities of wastewater treated in a number of alternative treatment systems. For simplification purposes, we have exogenously assigned abatement measures to specific existing wastewater treatment systems. Ideally, one would have significantly more data on existing treatment pathway types to support the incorporation of substitutable abatement measures when the investment decision is driven by cost minimization under country- and system-specific conditions.

The investment in large-scale public infrastructure required to improve wastewater treatment systems would not be determined solely by the carbon price associated with CH_4 emissions reductions. The public health benefits of such large-scale sanitation infrastructure projects greatly outweigh the potential benefits provided through any carbon market mechanism. However, the analysis presented here estimates the level of abatement that is technically achievable and the marginal costs of supplying reductions through these technologies, ignoring other potential positive externalities derived from putting these systems in place.

Finally, this chapter does not consider the potential impact of abatement measures applied to industrial wastewater treatment systems. The authors acknowledge that CH_4 emissions from industrial sources can be significant, and in some countries industrial wastewater emissions may represent more than half of total emissions associate with wastewater. However, data limitations, specifically information on the types of treatment systems employed in specific industries and correspondingly the abatement measures available to those systems is needed to estimate the abatement potential from industrial sources. International partnerships like the Global Methane Initiative (GMI) have begun to assess the level of CH_4 emissions available for recovery and use. Any future attempt to model abatement potential from the industrial wastewater sector would also require additional detail on the relative contribution of CH_4 emissions coming from domestic versus industrial wastewater sources.

References

Bogner, J., R. Pipatti, S. Hashimoto, C. Diaz, K. Mareckova, L. Diaz, P. Kjeldsen, S. Monni, A. Faaij, Q. Gao, T. Zhang, M. Abdelrafie Ahmed, R.T.M. Sutamihardja, and R. Gregory. 2008. "Mitigation of Global Greenhouse Gas Emissions from Waste: Conclusions and Strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. Working Group III (Mitigation)." *Waste Management Research* 26:11.

Buchanan, J.R. 2010. *Performance and Cost of Decentralized Unit Processes.* Publication No. DEC2R08. Alexandria, VA: Water Environment Research Foundation (WERF). Obtained at: http://ndwrcdp.werf.org/documents/DEC2R08/DEC2R08web.pdf.

Finney, B., and R. Gearheart. 2004. WAWTTAR: Water and Wastewater Treatment Technologies Appropriate for Reuse. Obtained at: http://firehole.humboldt.edu/wawttar/wawttar.html.

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 5: Waste; Chapter 6: Wastewater Treatment and Discharge.* Obtained at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_6_Ch6_Wastewater.pdf.

Scheehle, E.A., and M.R.J. Doorn. 2002. "Improvements to the U.S. Wastewater Methane and Nitrous Oxide Emissions Estimates." Working paper. USEPA: Washington, DC.

U.S. Environmental Protection Agency (USEPA). 2012b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2011*. Washington, DC: USEPA, Office of Solid Waste and Emergency Response. Obtained at: http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). 2012a. *Global Anthropogenic Non-CO*$_2$ *Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). 2009. *Municipal Wastewater Treatment Sector: Options for Methane Emission Mitigation* (Draft). Methane to Markets Administrative Support Group. Obtained at: http://www.globalmethane.org/documents/events_steer_20090910_scoping.pdf.

U.S. Environmental Protection Agency (USEPA). 1980. *Construction Costs for Municipal Wastewater Plants: 1973-1978*. Document EPA/430/9-80-003.

van de Guchte, C., and V. Vandeweerd. 2004. *Targeting Sanitation.* Our Planet, the Magazine of the United Nations Environment Programme (UNEP). Issue: Water, Sanitation, People. 14(4):19-21.

IV. Industrial Processes Sector

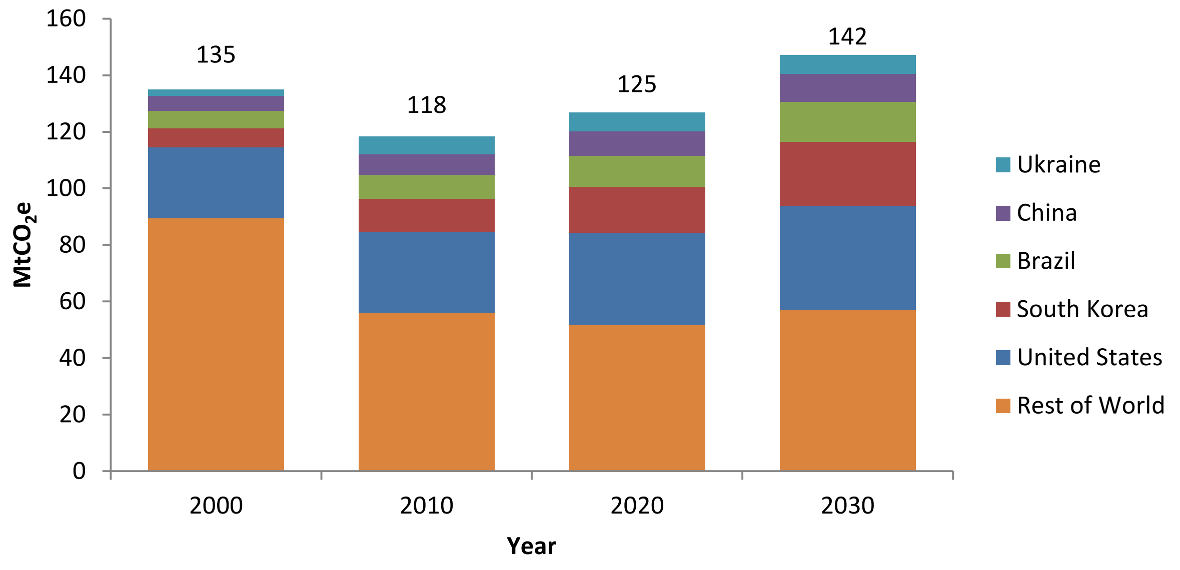
IV.1. Nitric and Adipic Acid Production

IV.1.1 Sector Summary

The production of nitric and adipic acid results in significant nitrous oxide (N_2O) emissions as a by-product. Nitric and adipic acid are commonly used as feedstocks in the manufacture of a variety of commercial products, particularly fertilizers and synthetic fibers (USEPA, 2012a).

Combined global emissions of N_2O from nitric and adipic acid production are shown in Figure 1-1. Globally, emissions have declined by about 13% (17 $MtCO_2e$) over the past decade; however, over the next 20 years—2010 to 2030—emissions are expected to increase steadily (~20%) growing by 24 $MtCO_2e$ over the time period. This trend is largely due to increased demand for fertilizer (nitric acid is an input) and increased demand for synthetic fibers (adipic acid is an input). In 2030, the United States, South Korea, Brazil, China, and Ukraine are expected to be five largest emitters of N_2O from nitric and adipic acid production.

Figure 1-1: N_2O Emissions from Nitric and Adipic Acid: 2000–2030

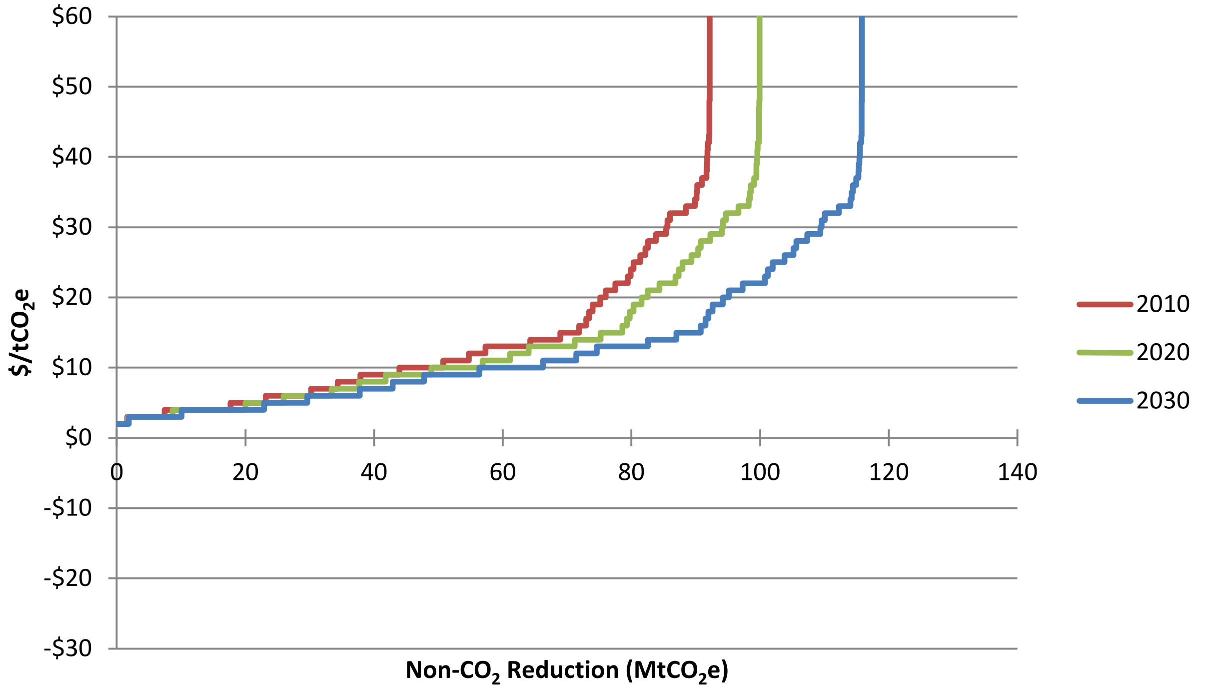


Source: USEPA, 2012a.

Over the coming decades, increased demand for adipic acid in Asia is expected to contribute to higher N_2O emissions from adipic acid production, while abatement control technologies employed at adipic acid production facilities in the 1990s in the United States, Canada, and some countries of the EU are expected to reduce N_2O emissions (USEPA, 2012a). Overall, increased global demand for adipic acid is expected to have the effect of higher annual N_2O emissions resulting from adipic acid production. In addition, global N_2O emissions from nitric acid are expected to increase as demand for nitrogen-based fertilizer increases. Although concerns about nutrient run-off have caused some countries to reduce their demand for nitrogen-based fertilizer, growing world demand for agricultural commodities is expected to have the effect of increasing nitric acid production and, consequently, N_2O emissions.

Global abatement potential of N_2O in nitric acid and adipic acid production is 98 and 115 $MtCO_2e$ in 2020 and 2030, respectively. These results are depicted in the sectoral marginal abatement cost (MAC) curves in Figure 1-2. As the MAC curves show, roughly 45% of the maximum abatement potential in each year is achievable at relatively low carbon prices (between \$2 and \$10 tCO_2e^{-1}).

Figure 1-2: Global MAC for Nitric and Adipic Acid: 2010, 2020, and 2030



The following section provides a brief explanation of the manufacturing processes that result in the formation of N_2O emissions. Next we discuss the projected emissions from these processes out to 2030. Subsequent sections characterize the abatement measures and present the cost of implementation and operation for each. The chapter concludes with a discussion of the MAC analysis approach unique to this sector and the regional results.

IV.1.2 N_2O Emissions from Nitric and Adipic Acid Production

N_2O emissions are closely correlated with the production of nitric and adipic acid. The following section discusses global production activity data, typical emissions factors, and baseline emissions estimates of N_2O from nitric and adipic acid production. The MAC analysis presented here starts by assuming the projected emissions presented in USEPA's 2012 Global Emissions Report (2012a). This analysis then derives industry activity from the USEPA emissions projections based on current industrial activity.

IV.1.2.1 Nitric Acid Production and Emission Factors

Ammonium nitrate production represents the largest demand market for nitric acid, with the majority of nitric acid being consumed by ammonium nitrate producers. The demand for ammonium nitrate products, especially fertilizer, is the main driver of nitric acid demand. Nitric acid production levels closely follow trends in fertilizer demand (Mainhardt and Kruger, 2000). Trends in fertilizer demand vary widely across different regions of the world. For example, in Western Europe, because of concerns over nutrient runoff and nitrates in the water supply, use of nitrogen-based fertilizer has been significantly reduced in the past couple of decades (USEPA, 2012a). Despite this trend, the European Fertilizer Manufacturers Association (EFMA) is predicting modest growth in demand of 1.3% annually over this decade. In other parts of the world, a continued desire to secure domestic fertilizer production capacity to supplant reliance on imports in combination with expansions in capacity for large fertilizer consuming countries are expected to result in a net increase in nitrogen-based fertilizer production capacity between 2010 and 2015 (IFA, 2011). Globally, over the next several decades, increases in food consumption and demand for agricultural products will continue to put upward pressure on fertilizer demand, which, in turn, is expected to increase the demand and consumption of nitric acid.

The actual number of nitric acid production plants globally is unknown. Previous reports cited by the Intergovernmental Panel on Climate Change (IPCC) have suggested the number to be between 255 and 600. More recent estimates suggest that between 500 and 600 plants were in operation in 2010 (Kollmus and Lazarus, 2010). The actual number is uncertain because many nitric acid plants are often part of larger integrated chemical facilities that manufacture products using nitric acid—in the production of a wide range of chemical products such as fertilizer and explosives (Kollmus and Lazarus, 2010; Mainhardt and Kruger, 2000).

As noted earlier, global nitric acid production is expected to increase over time. Projections in nitric acid production levels by country are not publicly available.

The IPCC reports that N_2O emissions factors for nitric acid production also remain relatively uncertain, because of a lack of information on manufacturing processes and emissions controls. The emissions factor is estimated, based on the average amount of N_2O generated per unit of nitric acid produced, combined with the type of technology employed at a plant. The IPCC uses a default range of 2 to 9 kilograms N_2O per ton of nitric acid produced. As a result, emissions factors for nitric acid production plants may vary significantly based on the operating pressure of the plant, the type of nitrogen oxide (NO_x) control technology (if any) deployed on the plant, and whether N_2O abatement has been implemented. As shown in Table 1-1, N_2O emission rates increase as the plant operating pressure increases. Furthermore, non-selective catalytic reduction (NSCR) is very effective at destroying N_2O, whereas other technologies used to control NO_x emissions, such as selective catalytic reduction (SCR) and extended absorption, do not reduce N_2O emissions.

Table 1-1: IPCC Emissions Factors for Nitric Acid Production

Production Process	N_2O Emissions Factor (relating to 100% pure acid)
Plants with NSCR[a] (all processes)	2 kg N_2O/tonne nitric acid ±10%
Plants with process-integrated or tailgas N_2O destruction	2.5 kg N_2O/tonne nitric acid ±10%
Atmospheric pressure plants (low pressure)	5 kg N_2O/tonne nitric acid ±10%
Medium pressure combustion plants	7 kg N_2O/tonne nitric acid ±20%
High pressure plants	9 kg N_2O/tonne nitric acid ±40%

Source: IPCC, 2006.

[a] Non-selective catalytic reduction (NSCR)

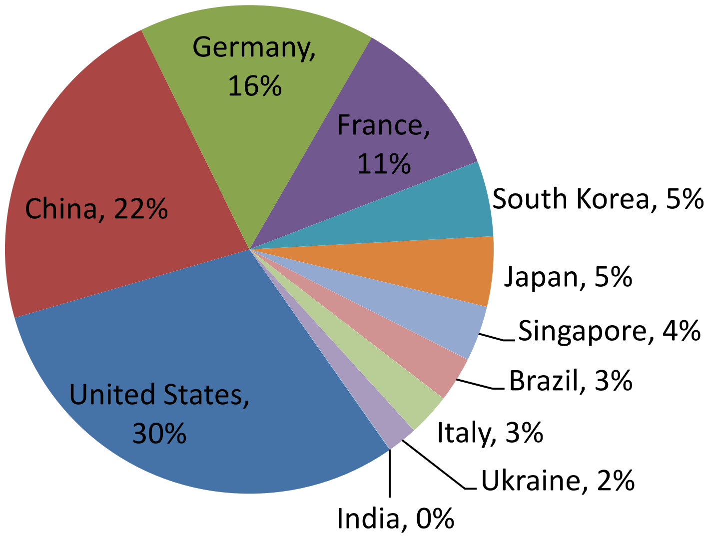
The IPCC notes that emissions factors as high as 19.5 kilograms N_2O per ton of nitric acid produced have been previously estimated. In addition, some estimates indicate that 80% of the nitric acid plants worldwide do not employ NSCR technology, which makes it more likely that the default range of potential emissions factors provided by the IPCC underestimates the true emissions baselines (Mainhardt and Kruger, 2000). Therefore, the uncertainties associated with these emission factors may be higher than listed in Table 1-1. However, no uncertainty assessments other than the IPCC's have been published, so without more information, this analysis relies on the published values above.

IV.1.2.2 Adipic Acid Production and Emission Factors

Adipic acid is used primarily in the production of synthetic fibers, predominantly as a precursor for the production on nylon 6,6 (The Chemical Company [CC], 2010a). As a result, production of adipic acid is closely correlated with the world's nylon production. Worldwide, the largest single use of adipic acid is in carpet manufacturing, accounting for 30% of the market (USEPA, 2012a; *Chemical Week*, 2007).

Global demand for adipic acid is expected to increase over the next few decades, particularly in Asia, driven primarily by the growth in demand for synthetic fibers (i.e., nylon 6,6), particularly for use in carpet manufacturing. Nylon 6,6 accounts for approximately 90% of adipic acid demand; demand for nylon is a strong indicator of future adipic acid demand (CC, 2010b). Future production of adipic acid is expected to closely following the demand trend for synthetic fibers. Figure 1-3 shows the share of adipic acid production capacity by country in 2010.

Figure 1-3: Adipic Acid Production Capacity by Country: 2010



Global capacity in 2010 was approximately 3 million metric tons, concentrated in the United States (30%), the European Union (29%), and China (22%) (Schneider, Lazarus, and Kollmuss, 2010; USEPA, 2012b). In the same year, global production of adipic acid was approximately 2.5 million metric tons (CC, 2010a). Plants in located in Canada and the United Kingdom were recently shut down and two of four facilities in the United States were idle in 2009 and assumed to remain so in 2010 (USEPA, 2012b).

The IPCC provides a default emissions factor of 300 kilograms ± 10% N_2O per ton of adipic acid produced (IPCC, 2006). This emissions factor assumes that no N_2O control system is in place. Additionally, this factor should be used only when national total data are available and plant-level data are deemed unreliable. This factor was developed using laboratory experiments measuring the reactionary stoichiometry for N_2O generation during the production of adipic acid (Mainhardt and Kruger, 2000). This emissions factor has been supported by some selected measurement at industrial plants. The IPCC recommends using plant-specific data for those plants with abatement controls already in place and reliable plant-level data (IPCC, 2006).

IV.1.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions from the production of nitric and adipic acid.[1] Historical emissions are characterized as those emissions released from the 1990 to 2010 period and projected emissions estimates cover the period from 2010 to 2030.

Historical Emissions Estimates

Between 1990 and 2005, N_2O emissions from nitric and adipic acid production decreased by 37% down from 200 $MtCO_2e$ in 1990 to 126 $MtCO_2e$ in 2005. Key factors that influence emissions are the demand for final products that include intermediates of nitric and adipic acid such as carpet and fertilizers. Although demand for and production of nitric and adipic acid increased over the 1990 to 2005 time period, N_2O emissions actually decreased over the period. The reductions in N_2O emissions over this period were mostly due to the installation of abatement technologies in the adipic acid industry (USEPA, 2012a).

Projected Emissions Estimates

Table 1-2 lists the combined projected N_2O baseline emissions from nitric and adipic acid production by country/region and year. Worldwide N_2O emissions are projected to increase by approximately 21% (24 $MtCO_2e$) between 2010 and 2030. South Korea, Canada, and Brazil are expected to experience the largest percentage increase in baseline emissions over the 2010 to 2030 period, with increases of 93, 77, and 68%, respectively. The United States is expected to have the second largest absolute increase (8 $MtCO_2e$) in emissions, which represents a 28% increase from 2010, while South Korea is expected to have the largest absolute increase (11 $MtCO_2e$).

IV.1.3 Abatement Measures and Engineering Cost Analysis

This analysis considered four abatement measures applied to the chemical processes used to produce nitric and adipic acid to reduce the quantity of nitrous oxide (N_2O) emissions released during the production process. Thermal destruction is the abatement measure applied to the adipic acid production process. The three remaining measures were applied to the nitric acid production process.

Nitric acid facilities have the option of using specially designed catalysts to control N_2O emissions. The location of catalyst placement within the nitric acid production process determines the catalyst design, composition, and terminology. Abatement measures applicable to nitric acid are characterized by where in the production process they are implemented. These options include primary abatement, secondary abatement, and tertiary abatement. Primary abatement measures occur within the ammonia burner, preventing the formation of N_2O. Secondary abatement measures such as homogeneous thermal decomposition and catalytic decomposition are installed at an intermediate point in the production process, removing the N_2O formed through ammonia oxidation. Tertiary abatement measures, such as catalytic decomposition and NSCR units are applied to the tail gas streams at the end of the nitric acid

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[1] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's *Global Emissions Projection Report.* Available at: http://www.epa.gov\climatechange\economics\international.html.

Table 1-2: Projected N_2O Baseline Emissions from Nitric and Adipic Acid Production: 2010–2030

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
United States	29	30	32	35	37	1.2%
South Korea	12	14	16	19	23	3.4%
Brazil	8	9	11	12	14	2.6%
China	7	8	9	10	10	1.6%
Ukraine	6	7	7	7	7	0.4%
Rest of Region						
Africa	3	3	3	4	3	0.1%
Central & South America	1	2	2	2	2	0.4%
Middle East	1	1	1	1	1	0.5%
Europe	32	25	25	25	29	−0.5%
Eurasia	7	7	7	7	7	0.2%
Asia	9	10	10	11	12	1.3%
North America	2	3	3	3	4	2.3%
World Total	**118**	**118**	**127**	**136**	**147**	**1.1%**

[a] CAGR = Compound Annual Growth Rate

[b] Mexico is the only country included under North America, as Canada and the United States are reported individually above.

Source: USEPA, 2012a.

production process. The implementation of one technology over another is driven largely by facility design constraints and/or cost considerations. The high operating costs of NSCR units and improvement in modern facility design will drive most future abatement projects to adopt secondary or tertiary catalysts over NSCR units.

This section briefly characterizes each abatement measure and the supporting technical assumptions that were used to compute the breakeven prices. Table 1-3 summarized the costs and technical assumptions for the four abatement measures. Abatement measure costs were derived from a variety of sources reporting in euros and dollars over a number of base years. For consistency, we assumed a fixed exchange rate of 1.32 (USD/EUR), and the Chemical Engineering Plant Cost Index (CEPI) was used to adjust costs for inflation. Consistent with other sectors evaluated in this study, the costs of abatement developed for this analysis exclude capital and O&M costs attributable to monitoring, reporting, and verification (MRV) activities.

IV.1.3.1 Adipic Acid—N_2O Abatement Methods

Adipic acid facilities typically direct the flue gas to a reductive furnace in a thermal destruction process to reduce nitric oxide (NO_X) emissions. Thermal destruction is the combustion of off-gases (including N_2O) in the presence of methane. The combustion process converts N_2O to nitrogen, resulting primarily in emissions of NO and some residual N_2O (Ecofys, Fraunhofer ISIR, and Öko-Institute, 2009). Facilities may also employee a catalytic decomposition method to abatement N_2O generated. The EU Emissions Trading System [ETS] and CDM methodologies for this abatement measure suggest that heat generated from the decomposition of N_2O can be used to produce process steam for utilization in local processes, substituting for more expensive steam generated using fossil fuel alone. For this analysis, we assume the abatement measures' conversion of N_2O to nitrogen technical effectiveness is 95%. Costs presented below are based on a catalytic decomposition method.

Table 1-3: Abatement Measures for Nitric and Adipic Acid Production

	2010 USD				Annual Benefits		
Abatement Option	Total Installed Capital Cost	Annual O&M Cost	Time Horizon (Years)	Technical Efficiency,%	Energy	Non-energy	Average Reductions (tCO_2e/yr)
Adipic Acid Production[a]							
Thermal/catalytic decomposition	11.4	2.2	20	96%	—	0.3	**4,206,218**
Nitric Acid Production[b]							
Secondary Abatement— Catalytic decomposition in the burner	1.3	0.4	15	85%	—	—	**779,571**
Tertiary Abatement— Direct catalytic decomposition	2.3	0.2	15	95%	—	—	**871,286**
Tertiary Abatement— Non-selective catalytic reduction unit	4.0	2.1	20	95%	—	—	**871,286**

[a] Based on adipic acid plant capacity of 200 metric tons of adipic acid per day.

[b] Based on nitric acid plant capacity of 1,000 $tHNO_3$/day.

- **Capital Costs:** Initial capital costs are $156 per metric ton of production capacity in 2010 dollars. This cost includes the costs of engineering design and process modifications in addition to equipment and installation costs. Assuming a plant with capacity of 200 tonnes adipic acid production per day, the initial capital cost would be approximately $11.4 million (2010 USD).
- **Annual O&M Costs:** Annual costs total $38 per metric ton of production in 2010 dollars, which includes the costs of annual energy requirements and system maintenance. Assuming a plant with capacity of 200 tonnes and a utilization factor of 80%, the annual operating cost would be $2.2 million (2010 USD). Catalyst consumption represents 60% of the annual costs.
- **Annual Benefits:** Steam produced through the decomposition of N_2O under this abatement measure can offset steam generated using more expensive energy sources providing a fuel cost savings. These annual benefits can equal up to 60% of operating costs (Ecofys et al., 2009). This analysis assumes a more conservative estimate of 16% of operating costs or $5.6 per metric ton of adipic acid production based on CDM project documentation.
- **Applicability:** This option applies to adipic acid production facilities that do not currently control N_2O emissions. Based on recent analysis (Schneider et al., 2010), only 9 of the 23 operational facilities in 2010 had unabated N_2O emissions.
- **Technical Effectiveness:** This analysis assumes a 95% efficiency converting N_2O into nitrogen and water.
- **Technical Lifetime:** 20 years

IV.1.3.2 Nitric Acid—Primary Abatement Measures

This group of abatement measures can be applied at the ammonia oxidation stage of the nitric acid production process. Perez-Ramirez (2003) identified three alternative approaches categorized as primary abatement options: optimized oxidation, modification of the Pt-Rh gauzes, and oxide-based combustion catalysts. All three technologies prevent the formation of N_2O in the ammonia burner and would require making adjustments to the ammonia oxidation process and/or catalyst (Perez-Ramirez, 2003). Although the primary abatement technology options are technically feasible, they are not modeled in this analysis because of a lack of technology cost data and the fact that the alternative options discussed below achieve greater abatement and are better defined.

IV.1.3.3 Nitric Acid—Secondary Abatement Measures

Secondary abatement measures remove N_2O immediately following the ammonia oxidation stage, between the ammonia converter and the absorption column (Perez-Ramirez, 2003). Abatement measures include thermal decomposition, catalytic decomposition inside or immediately following the ammonia burner. Thermal decomposition, developed by Norsk Hydro in the 1990s, is better suited for inclusion in new plants, because it requires redesigning the reaction chamber immediately following the ammonia burner. This design change can increase the capital cost of a new plant by 5 to 6% but has no impact on operating costs (Perez-Ramirez, 2003). The catalytic decomposition option is better suited for retrofitting and can be incorporated as an add-on technology at minimal cost. For this analysis, the catalytic decomposition costs were used as the representative costs of the secondary abatement option.

- **Capital Costs:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumes a capital cost of \$3.5/tonne of HNO_3 production capacity[2] and a plant capacity of 1,000 $tHNO_3$/day. Using these assumptions, the initial capital costs would equal \$1.3 million (2010 USD).
- **Annual O&M Costs:** Annual costs include catalyst replacement and recycling of spent catalyst, replacement of spare catalyst, and loss of production due to catalyst disruptions. This analysis assumes an annual cost of \$1.3/$tHNO_3$ produced and a plant utilization rate of 90% (Perez-Ramirez, 2003). Following the plant example of a 1,000 $tHNO_3$/day, the annual cost would be \$0.4 million (2010 USD).
- **Annual Benefits:** No benefits are associated with this option.
- **Applicability:** This option is applicable to all existing nitric acid plants.
- **Technical Effectiveness:** This analysis assumes an 80% efficiency converting N_2O into nitrogen and water.
- **Technical Lifetime:** 20 years

IV.1.3.4 Nitric Acid—Tertiary Abatement Measure: Direct Catalytic Decomposition

Tertiary abatement measures are located after the absorption tower where tail gas leaving the absorption column is treated to destroy N_2O (Perez-Ramirez, 2003). Similar to earlier abatement measures, this measure reduces the N_2O into nitrogen and oxygen, through thermal or catalytic decomposition.

- **Capital Costs:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumes a capital cost of \$6.3/tonne of HNO_3 production capacity[3] and a plant capacity of 1,000 $tHNO_3$/day. Using these assumptions, the initial capital costs would equal \$2.3 million (2010 USD).

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[2] Based on costs of € 0.25/$tHNO_3$ reported in 2008 euros (EC, 2008) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI) and an exchange rate of 1.32 (USD/EUR).

[3] Based on costs of € 0.5/ $tHNO_3$ reported in 2008 euros (EC, 2008) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI) and an exchange rate of 1.32 (USD/EUR).

- **Annual O&M Costs:** Annual costs include catalyst replacement and recycling of spent catalyst; replacement of spare catalyst; loss of production due to catalyst disruptions or the lowering of the process pressure. This analysis assumes an annual cost of \$0.6/tHNO_3 produced and a plant utilization rate of 90% (Perez-Ramirez, 2003). Following the plant example of a 1,000 tHNO_3/day, the annual cost would be \$0.2 million (2010 USD).
- **Annual Benefits:** Minor benefits are associated with this option. Decomposition is an exothermic process, so a small amount of heat could be recovered from the process and converted to steam. However, the costs of the equipment needed to recover the heat and convert it to steam could outweigh the benefit. The ability to accrue benefits would also be limited by the amount of space available to add the equipment.
- **Applicability:** This option is applicable to most existing nitric acid plants but is highly dependent on site-specific factors, such as age of the facility and the footprint of the facility. Tertiary abatement measures may require additional space and additional equipment.
- **Technical Effectiveness:** The analysis assumes a 82% efficiency converting N_2O into nitrogen and water.
- **Technical Lifetime:** 20 years

IV.1.3.5 Nitric Acid—Tertiary Abatement Measure: Non-selective Catalytic Reduction (NSCR)

One specialized type of tertiary catalyst is an NSCR system. The NSCR typically costs more than other types of tertiary catalysts because it requires a reagent fuel, such as natural gas, propane, butane, or hydrogen, to reduce NO_X and N_2O over a catalyst. If an NSCR system is used at a nitric acid plant that is collocated with other chemical processes, the costs of these reagent fuels may be lessened. For example, if ammonia is produced near the nitric acid production plant, the waste gas stream from ammonia production is a hydrogen-rich gas stream that could be used as the reagent fuel for an NSCR.

- **Capital Costs:** Capital costs include the purchase and installation of the NSCR unit and catalyst. This analysis assumes a capital cost of \$12.6/tonne of HNO_3 production capacity based on \$8.2/tHNO_3 reported in 1991 USD (USEPA, 1991) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI). Assuming a plant capacity of 1,000 tHNO_3/day, the initial capital cost would equal \$4.6 million (2010 USD).
- **Annual O&M Costs:** Annual costs total \$8.8/tHNO_3 produced. Annual costs include the cost of reagent fuel, labor, maintenance, and other fixed costs for capital recovery and insurance. Total annual cost for the example plant would be \$2.9 million per year (2010 USD).
- **Annual Benefits:** Energy benefits are associated with this option. The NSCR reaction is exothermic, which means that the reaction generates heat. This heat can be recovered and converted into steam for use as an energy source.
- **Applicability:** This option is applicable to all nitric acid production facilities without existing tertiary abatement measures. Although it is theoretically possible to employ multiple abatement measures, the likelihood of multiple retrofitted abatement measures operating together in an efficient manner is very low.
- **Technical Effectiveness:** The analysis assumes 90% efficiency converting N_2O into nitrogen and water.
- **Technical Lifetime:** 20 years

IV.1.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the N_2O abatement measures for nitric and adipic acid production facilities.

IV.1.4.1 Methodological Approach

The MAC analysis is based on project costs developed for a set of model facilities based on the abatement measure costs discussed in Section IV.1.3. Similar to the steps taken in other sectors, we developed an inventory of facilities that are representative of existing facilities. Next we applied the abatement costs to calculate the break-even prices for each option and applicable facility pair. Finally, the model estimates the mitigation potential based on the country-specific share of emissions attributed to nitric versus adipic acid production. This analysis takes the N_2O emissions projections (given) and allocates emissions based on production process to derive the model facility inventories.

Adipic acid facilities are defined through a detailed inventory of the 23 production facilities worldwide operating in 2010. While no comprehensive inventory was available for nitric acid plants, it is believed that there are roughly 500 to 600 nitric acid plants globally (Kollmuss and Lazarus, 2010). Instead, we developed a series of 4 model nitric acid production units based on plant characteristics obtained from a detailed inventory of 67 nitric acid plants that varied in age and production processes.[4]

Adipic Acid—Facility inventory

The first step in the analysis was to determine the allocation of projected emissions to nitric and adipic acid production by country. For example, in the United States, adipic acid production accounted for approximately 15% of total baseline emissions in 2010, while the majority of emissions were attributed to nitric acid production. Once the share of baseline emissions is determined, the MAC model can assess the abatement potential on the technically applicable pool of emissions available for abatement.

To estimate the technically applicable share of emissions, we developed a detailed inventory of operational adipic acid plants in 2010. Adipic acid plants were used as the starting point because the number of international adipic acid plants is small (<30 globally), supported by recent literature providing detail on existing plants in 2010 obtained from Schneider, Lazarus, and Kollmuss (2010). The detailed inventory includes 23 adipic acid production facilities operating in 11 countries totaling approximately 3,000 kt of production capacity.[5] Schneider and co-authors also identified the N_2O abatement technologies and plant utilization factors. Figure 1-4 summarizes the global adipic acid production capacity breakdown by country, and facility counts are reported in parenthesis after the country labels. The bottom-up inventory was used to estimate N_2O emission from adipic acid production by country.

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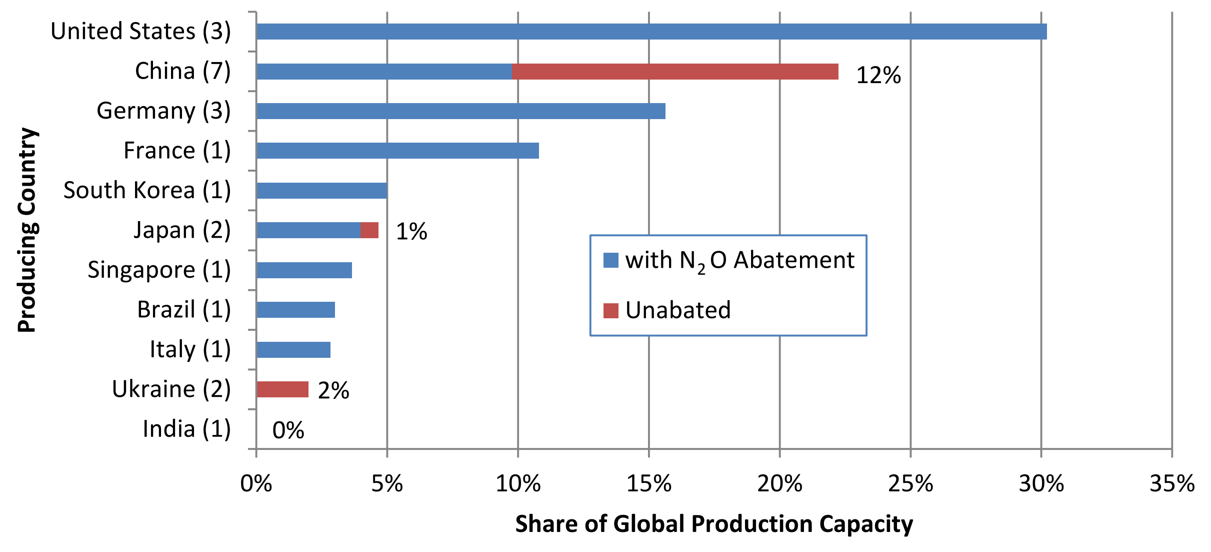
[4] While there are a number of different processes employed at nitric acid production facilities, single-pressure plants are much more common in the United States. Based on information gathered, most nitric acid production plants were constructed to maximize the yield from stages two and three of the production process and, therefore, operate at high pressures.

[5] Major changes to previously reported adipic acid inventories (Mainhardt and Kruger, 2000; Organisation for Economic Co-operation and Development [OECD], 2004) includes the opening of 5 new plants in China between 2008 and 2009; and the closure of two plants located in Canada and the United Kingdom. In addition, a fourth plant located in the United States was idle between 2008 and 2009 and assumed to continue to idle in 2010 (USEPA, 2012b).

Figure 1-4: Operational Adipic Acid Production Facilities in 2010 by Share of Global Capacity



Source: Adapted from Schneider et al. 2010.

Note: Facility counts are listed in parentheses beside country name.

Although 11 countries currently produce adipic acid, only 4 countries (China, Ukraine, Japan, and India) have operational facilities that are known to have no N_2O emission controls in place. As the figure shows, all but 15% of the adipic acid capacity has N_2O abatement controls in place. The 15% of capacity with no N_2O abatement controls is represented by the nine smallest facilities in the industry located in China (5), Ukraine (2), Japan (1), and India (1).

In the 1990s, most of the adipic acid producers in developed countries voluntarily adopted N_2O abatement measures (Schneider et al., 2010; EcoFys, 2009, USEPA, 2012b). In 2005, with the establishment of the CDM methodology for crediting N_2O abatement projects at adipic acid plants, producers in developing countries began to adopt N_2O abatement measures. Schneider and co-authors point out that although the CDM methodology was effective in achieving N_2O reductions in developing countries, it was limited to facilities that were in operation prior to 2005.

Since 2005, much of the growth in adipic acid production capacity has been in China, with five plants coming online between 2008 and 2009 (Schneider et al., 2010). Future growth is also projected to be highly concentrated in Asia (Global Industry Analysts Inc. [GIA], 2010). China alone is expected to see its capacity more than double in the near term with five new adipic acid plants between 2011 and 2013 (Zhao, 2011).

Only 15% of global capacity continues to operate with no known N_2O abatement. China and Ukraine account for over 95% of the capacity with unabated N_2O emissions. In China, the five plants operating without abatement controls account for two-thirds of the country's total adipic acid capacity. For this analysis, we assume that future abatement potential is limited to the nine plants identified as having no known N_2O abatement measure in place.

Although no information was available on specific plant utilization rates, we assume utilization rates of 60% for all non-CDM facilities, 85% for CDM facilities,[6] and 45% for non-CDM facilities in other parts of Asia (Schneider et al., 2011). Combining plant capacities and corresponding utilization rates yields a total adipic acid production in 2010 of 1.84 million metric tons.

Next we estimate net emissions for each country by applying the IPCC emissions factor of 300 kg N_2O per metric ton of adipic acid produced to the plant production estimated above. Net emissions estimated account for existing abatement activity assuming a control efficiency of 96%. This analysis yields net emissions by country totaling 103,800 tonnes of N_2O (32.2 $MtCO_2e$) in 2010.

We assume the net emissions calculated for each country represents adipic acid's representative share of total projected baseline emissions (see Table 1-2). Table 1-4 provides the percentages used to breakout the N_2O emissions baseline to adipic acid.

The analysis assumes that N_2O emissions from adipic acid production account for the percentage of total sectoral baseline listed in Table 1-4. We attribute the balance of baseline emissions to nitric acid production.

Table 1-4: Adipic Acid-Producing Countries' Share of Baseline Emissions[a]

	Share of N_2O Baseline, %	
Country	**Adipic Acid**	**Nitric Acid**
Brazil	5	95
China[b]	36	64
France	30	70
Germany	21	79
India	1	99
Italy	27	73
Japan[b]	36	64
Singapore	25	75
South Korea	5	95
Ukraine[b]	36	64
United States	15	85
Other Countries	0	100

[a] For China, Japan, and Ukraine, the more detailed inventory-based estimate of emissions developed for this analysis yielded emission values greater than the total baseline projections for 2010. Hence, we defaulted back to percentages assumed for the previous report (36%).

[b] China, Japan, and Ukraine percentages used are from EMF 21 MAC model (USEPA, 2006).

Model Facility Description for Nitric Acid

While it is believed that there are roughly 500 to 600 nitric acid plants globally (Kollmuss and Lazarus, 2010), no comprehensive inventory was available for nitric acid plants. Instead, we developed a series of 4 model nitric acid production units based on plant characteristics obtained from a detailed inventory of 67 nitric acid plants that varied in age and production processes. We organize the model facilities based on production capacity. All four facility types are assumed have an uncontrolled

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[6] Facilities located in Brazil, China, and South Korea.

emissions factor of 8.5 kg N_2O per $tHNO_3$ produced[7] (IPCC, 2006). Table 1-5 summarizes the model facilities for nitric acid production by capacity and resulting annual N_2O emissions.

Table 1-5: Model Nitric Acid Facilities Assumptions

Model Plants	Production ($tHNO_3$/yr)	Annual N_2O Emissions (uncontrolled) (tN_2O)
Small	30,600	261
Medium	113,333	968
Large	226,667	1,936
Modern plant	340,000	2,904

Estimate Abatement Project Costs and Benefits

Abatement measure costs and technical efficiencies were applied to each of the model facilities to estimate the break-even prices. Based on facility characteristics, we estimate the abatement project costs and calculated the break-even prices. Table 1-6 summarizes the break-even price calculation for nitric and adipic acid production facilities.

Table 1-6: Example Break-Even Prices for N_2O Abatement Measures

Abatement Option	Reduced Emissions ($MtCO_2e$)	Annualized Capital Costs ($/$tCO_2e$)	Annual Cost ($/$tCO_2e$)	Annual Revenue ($/$tCO_2e$)	Tax Benefit of Depreciation ($/$tCO_2e$)	Break Even Price ($/$tCO_2e$)
Adipic Acid Production						
Thermal destruction	9.2	0.22	1.15	1.12	0.04	0.21
Nitric Acid Production						
Secondary Abatement— Catalytic decomposition in the burner	0.8	0.4	0.6	0.0	0.1	0.86
Tertiary Abatement— Tailgas catalytic decomposition	0.9	0.5	0.2	0.0	0.1	0.67
Tertiary Abatement— NSCR unit	0.9	1.0	3.3	0.0	0.2	4.19

Note: Break-even price assumes 10% discount rate and 40% tax rate.

Thermal destruction based on adipic acid production capacity of 75 kt yr^{-1} and nitric acid options based on 328kt HNO_3 yr^{-1} production capacity.

IV.1.4.2 MAC Analysis Results

Global abatement potential of N_2O emissions in nitric and adipic acid production is 78% of annual emissions. The majority of abatement potential is associated with nitric acid production because of the high degree of abatement already occurring at adipic acid facilities. Table 1-7 and Figure 1-5 present the MAC curve results for 2030 showing a cumulative reduction potential of 111 $MtCO_2e$.

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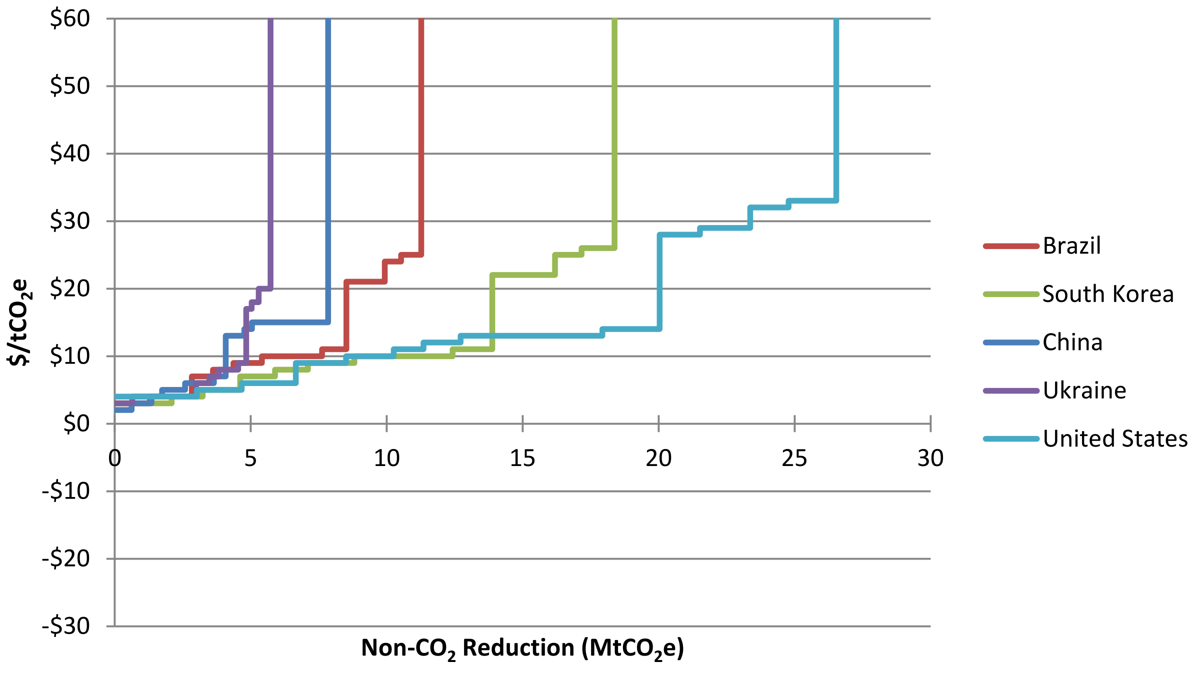
[7] The default emissions factor for the high pressure process is 9 kg N_2O per ton of nitric acid; the default emissions factor for medium pressure processes is 7 kg N_2O per ton of nitric acid produced.

Table 1-7: Abatement Potential by Region at Selected Break-Even Prices in 2030

	Break-Even Price ($/tCO$_2$e)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Brazil	—	—	—	2.8	7.6	8.5	8.5	11.3	11.3	11.3	11.3
China	—	—	—	2.6	4.1	7.8	7.8	7.8	7.8	7.8	7.8
South Korea	—	—	—	4.6	12.4	13.9	13.9	18.4	18.4	18.4	18.4
Ukraine	—	—	—	3.0	4.8	4.8	5.7	5.7	5.7	5.7	5.7
United States	—	—	—	4.7	10.3	20.0	20.0	23.4	26.5	26.5	26.5
Rest of Region											
Africa	—	—	—	1.4	2.0	2.7	2.7	2.7	2.7	2.7	2.7
Central and South America	—	—	—	0.3	0.9	1.0	1.1	1.3	1.3	1.3	1.3
Middle East	—	—	—	0.2	0.5	0.6	0.6	0.8	0.8	0.8	0.8
Europe	—	—	—	4.3	12.2	16.4	18.9	20.8	23.2	23.2	23.2
Eurasia	—	—	—	2.9	4.6	6.0	6.0	6.1	6.1	6.1	6.1
Asia	—	—	—	2.3	5.5	6.6	7.5	8.4	8.8	8.8	8.8
North America	—	—	—	0.6	1.3	2.3	2.4	2.8	3.1	3.1	3.1
World Total	**0.0**	**0.0**	**0.0**	**29.6**	**66.3**	**90.8**	**95.1**	**109.6**	**115.8**	**115.8**	**115.8**

Figure 1-5: Marginal Abatement Cost Curve for Top 5 Emitters in 2030



A majority of abatement potential spans over 30 nitric acid-producing countries, and only a small fraction of abatement potential associated with adipic acid production is limited to adipic acid plants in China, Ukraine, and India. Total reduction potential is achieved at break-even prices between $0 and $50/tCO₂e.

IV.1.4.3 Uncertainties and Limitations

This analysis leverages new data from public sources to improve on the facility-level detail used in developing abatement project costs. In addition, we have incorporated a comprehensive international inventory of current adipic acid production facilities. However, additional date and detail would improve our abatement potential estimates.

- Abatement technology utilization rates: Active CDM and Joint Implementation (JI) abatement projects in this sector have reported N_2O reduction efficiencies and utilization rates significantly higher than the default assumptions provided by the IPCC.
- Technology applicability across various nitric acid production processes and better understanding of how cost for abatement measures would vary with each process.
- Improved estimates of regional changes in production over the next 20 to 30 years. For example expected increases in Chinese adipic acid production capacity out to 2015, assuming no abatement measures are installed would have significant impacts on both emission projections and abatement potential in some countries.

References

The Chemical Company (CC). 2010a. "About Adipic Acid." Jamestown, RI: The Chemical Company.

The Chemical Company (CC). 2010b. "Adipic Acid Overview." Jamestown, RI: The Chemical Company.

Ecofys, Fraunhofer ISIR (Institute for Systems and Innovation Research), and the Öko-Institute. 2009. *Methodology for the Free Allocation of Emission Allowances in the EU ETS Post 2012* (pp. 6–20, and 42–48). European Commission. Obtained at: http://ec.europa.eu/clima/policies/ets/benchmarking/docs/bm_study-chemicals_en.pdf.

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 3 Industrial Processes and Product Use.* Obtained at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_3_Ch3_Chemical_Industry.pdf.

International Fertilizer Industry Association (IFA). 2011. Fertilizer Outlook 2011 – 2015. 79th IFA Annual Conference. Montreal (Canada), 23-25 May 2011.

Global Industry Analysts Inc. (GIA) 2011. Global Adipic Acid Market to Reach 5.5 Billion Pounds by 2015, According to a New Report by Global Industry Analysts, Inc. Obtained on March 11, 2011 at: http://www.prweb.com/releases/2011/1/prweb8043623.htm.

Heffer, P., & Prud'homme, M. (2011). *Fertilizer Outlook 2011–2015*. (A/11/69) Presented at the 79th IFA Annual Conference, Montreal, Canada: International Fertilizer Industry Association (IFA). Obtained on April 2, 2012 at: http://www.fertilizer.org/ifa/HomePage/LIBRARY/Publication-database.html/Fertilizer-Outlook-2011-2015.html.

Kollmuss, A., and M. Lazarus. 2010. "Industrial N_2O Projects Under the CDM: The Case of Nitric Acid Production" (Working Paper No. WP-US-1007). Somerville, MA: Stockholm Environment Institute (SEI). Obtained at: http://www.sei-international.org/mediamanager/documents/Publications/Climate/sei-nitricacid-9nov2010.pdf.

Mainhardt, H. and D. Kruger. 2000. "N_2O Emissions from Adipic Acid and Nitric Acid Production." *Good Practice and Uncertainty Management in National Greenhouse Gas Inventories.* Montreal: Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme. Obtained at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_2_Adipic_Acid_Nitric_Acid_Production.pdf.

Organisation of Economic Cooperation and Development (OECD). 2004. *SIDS Initial Assessment Report For SIAM 18 Adipic Acid*. Paris, France. Obtained at: http://www.inchem.org/documents/sids/sids/124049.pdf.

Pérez-Ramírez, J., Kapteijn, F., Schöffel, K., & Moulijn, J. A. 2003. "Formation and control of N_2O in nitric acid production: Where do we stand today?" *Applied Catalysis B: Environmental*, 44(2), 117–151. doi:10.1016/S0926-3373(03)00026-2.

Schmidt, D.V. and M. von Velsen-Zerweck. 2010. "N_2O emissions from nitric acid plants in CDM and JI projects." *Nitrogen+Syngas*, 307, 43 –47.

Schneider, L., M. Lazarus, and A. Kollmuss. 2010. "Industrial N_2O Projects Under the CDM: Adipic Acid—A Case of Carbon Leakage?" (Working Paper No. WP-US-1006). Somerville, MA: Stockholm Environment Institute (SEI). Obtained at: http://ec.europa.eu/clima/consultations/0004/unregistered/cdm_watch_2_en.pdf.U.S. Environmental Protection Agency (USEPA). 1991. *Alternative Control Techniques Document—Nitric and Adipic Acid Manufacturing Plants.* EPA-450/3-91-026. USEPA: Research Triangle Park, NC. Obtained at: http://www.epa.gov/ttn/catc/dir1/nitric.pdf.

U.S. Environmental Protection Agency (USEPA). 2011. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009.* USEPA: Washington DC. As obtained on March 15, 2011. Obtained at: http://epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). 2012a. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. USEPA: Washington DC. Obtained at: http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html.

U.S. Environmental Protection Agency (USEPA). 2012b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010.* USEPA: Washington DC. As obtained on March 19, 2012. Obtained at: http://epa.gov/climatechange/emissions/usinventoryreport.html.

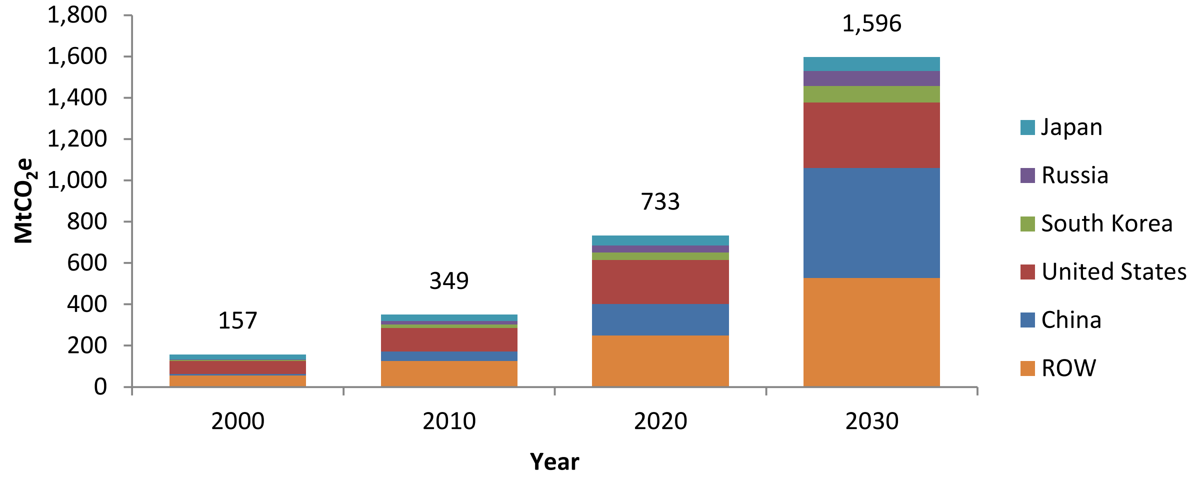
Zhao, D. November 7, 2011. "China Adipic Acid Tumbles 36% on Weak Demand from PU Sector." Market news article from ICIS.com. Obtained March 28, 2012, at: http://www.icis.com/Articles/2011/11/07/ 9505810/china-adipic-acid-tumbles-36-on-weak-demand-from-pu-sector.html.

IV.2. HFC Emissions from Refrigeration and Air Conditioning

IV.2.1 Sector Summary

A number of hydrofluorocarbons (HFCs) are used in refrigeration and air conditioning (AC) systems and are emitted to the atmosphere during equipment operation, repair, and disposal, unless recovered, recycled and ultimately destroyed. The most common HFCs include HFC-134a, R-404A, R-410A, R-407C, and R-507A.[1] In response to the ozone depleting substance (ODS) phaseout, equipment is being retrofitted or replaced to use HFC-based substitutes or intermediate substitutes (e.g., hydrochlorofluorocarbons [HCFCs]) that will eventually need to be replaced by HFCs or other non-ozone-depleting alternatives. Greenhouse gas (GHG) emissions from the refrigeration/AC sector (excluding chlorofluorocarbons (CFCs) and HCFCs) were estimated at roughly 349 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010. By 2020, emissions from this sector are expected to reach 733 million $MtCO_2e$, as shown in Figure 2-1. A majority of the growth will result from increased use of HFCs in developing countries.

Figure 2-1: HFC Emissions from Refrigeration and AC: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012.

This analysis reviews options to reduce emissions from the refrigeration/AC sector by using low-global warming potential (GWP) refrigerants, low-emission technologies, and improved practices to properly recover refrigerant at equipment servicing and disposal.

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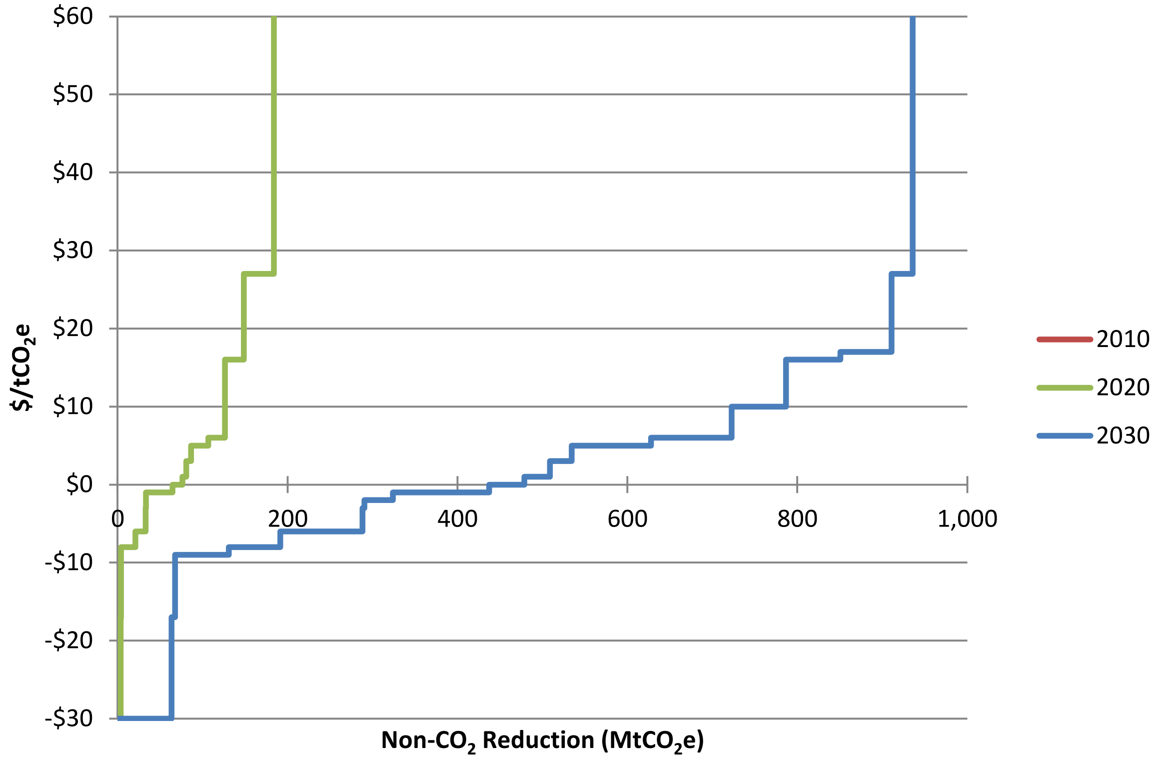
[1] R-404A, R-410A, R-407C, and R-507A refrigerant blends are composed of HFCs. Specifically, R-404A is 44% by weight HFC-125, 52% HFC-143a, and 4% HFC-134a,. R-410A is 50% HFC-32 and 50% HFC-134a. R-407C is 23% HFC-32, 25% HFC-125, and 52% HFC-134a. R-507A (also called R-507) is 50% HFC-125 and 50% HFC-143a.

Global abatement potential from refrigeration and AC in 2030 as evaluated in this analysis equates to approximately 70% of total annual emissions from refrigeration and AC end-uses and 28% of total emissions from ODS substitutes. In the near-term, abatement opportunities within refrigeration and AC are partially limited because many of the abatement options identified apply only to newly manufactured equipment and are thus limited by the turnover rate of the existing refrigeration and AC stock. In addition, this analysis does not explore new equipment abatement options for all refrigeration and AC equipment types, although such options may exist. Marginal abatement cost (MAC) curve results are presented in Figure 2-2. Maximum abatement potential of the options in the refrigeration and AC sector explored in this analysis is 540 $MtCO_2e$ in 2030. There are 317 $MtCO_2e$ of emissions reductions available in 2030 that are cost-effective at currently estimated prices.

Figure 2-2: Global Abatement Potential in Refrigeration and AC: 2010, 2020, and 2030



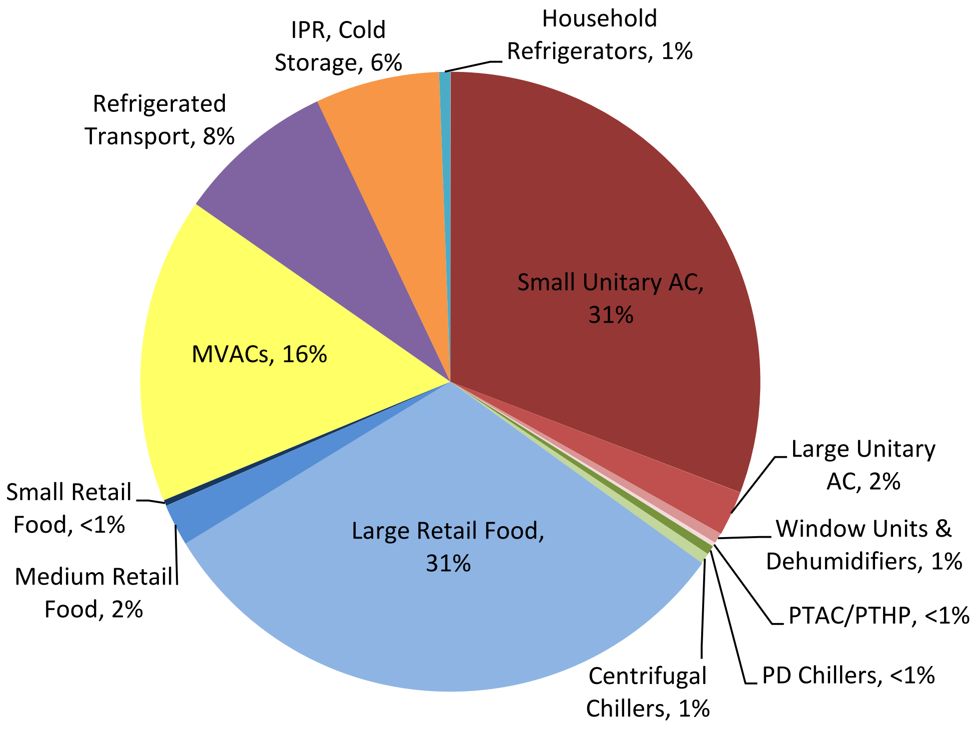
IV.2.2 Emissions from Refrigeration and Air Conditioning

HFC emissions from refrigeration/AC occur during equipment manufacturing; as equipment is filled with coolant; during use, as a result of component failure, leaks, and purges; during servicing; and at the time of disposal, if the remaining refrigerant charge is not properly recovered. The use of refrigeration and AC equipment also generates indirect emissions of GHGs (primarily carbon dioxide) from the generation of power required to operate the equipment. HFC emissions can be reduced by adopting alternative technologies (that either reduce HFC leakage or substitute the refrigerant for a low/no GWP option) and by improving technician practices for equipment maintenance/servicing and disposal.

For the purpose of this analysis, the sector is characterized by six major end-use types, presented in descending order of 2020 GWP-weighted HFC emissions internationally (see Figure 2-3):

- *residential and commercial AC,* including window units and dehumidifiers, large and small unitary air conditioners (including both ducted and non-ducted split systems), centrifugal and positive displacement chillers, and packaged terminal air conditioners and packaged terminal heat pumps (PTAC/PTHP), used to regulate the temperature and reduce humidity in homes, apartment buildings, offices, hotels, shopping centers, and other large buildings, as well as in specialty applications such as ships, submarines, nuclear power plants, and other industrial applications;
- *retail food refrigeration*, including small commercial refrigerators/freezers; medium-sized condensing units found in convenience stores, restaurants, and other food service establishments; and large systems found in supermarkets;
- *motor vehicle air-conditioning (MVAC)* used in cars, trucks, and buses;
- *refrigerated transport*, including refrigerated vans/trucks, containers, ship holds, truck trailers, railway freight cars, and other shipping containers;
- *industrial process refrigeration (IPR)* and *cold storage warehouses,* including complex refrigeration systems used in the food/beverage production, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries as well as refrigeration systems used to cool meat, produce, dairy products, and other perishable goods that are in storage; and
- *household refrigerators and freezers* used primarily in residential buildings.

Figure 2-3: Global HFC Emissions in 2020 by Application Type (% of GWP-Weighted Emissions)



For the purpose of this analysis, the sector considers nine facilities and/or applications, as defined below.

- MVAC system used in a typical passenger car; for cost modeling purposes, this system is characterized as having a charge size of 0.77 kg of R-134a.
- Large retail food refrigeration system used in a typical supermarket (assumed 60,000 sq. ft.); for cost modeling purposes, this facility is characterized as having a charge size of 1,633 kg of R-404A.
- Small retail food equipment (e.g., stand-alone systems) typically used in supermarkets and convenience stores; for cost modeling purposes, this equipment is characterized as having a charge size of 0.5 kg of 90% R-134a and 10% R-404A (based on the average HFC refrigerant types currently installed in the U.S. market).
- Window AC unit or dehumidifier; for cost modeling purposes, this unit is characterized as having a charge size of 0.4 kg of R-410A.
- Unitary AC system or PTAC/PTHP; for cost modeling purposes, this system is characterized as having a charge size of 8 kg of R-410A.
- Positive displacement chiller (i.e., screw or scroll chiller); for cost modeling purposes, this equipment is characterized as having a charge size of 270 kg of 33% R-410A, 33% R-407C, and 33% R-134a (based on the average HFC refrigerant types currently installed in the U.S. market).
- IPR/cold storage system;[2] for cost modeling purposes, this system is characterized as having a charge size of 2,000 kg using 25% R-507A, 25% R-404A, 25% R-134a, and 25% R-410A (based on the average HFC refrigerant types currently installed in the U.S. market).
- Typical auto disposal yard using a recovery device to recover refrigerant from MVACs; for cost modeling purposes, this facility is characterized as recovering refrigerant from about 425 MVACs per year (with an average of 0.13 kg of R-134a recoverable per MVAC).
- Typical auto service shop using a recovery/recycling device to service MVACs; for cost modeling purposes, this facility is characterized as recovering refrigerant from about 150 MVACs per year (with an average 0.29 kg of R-134a recoverable per MVAC).

For modeling purposes, data typical for U.S. systems/equipment are used. Certain cost assumptions, such as labor rates, energy prices and capital costs, are adjusted for other regions.[3] Otherwise, it is assumed that the costs and reductions achieved in the United States can be scaled and are representative of the costs and reductions in other regions.

IV.2.2.1 Activity Data or Important Sectoral or Regional Trends

Refrigeration/AC consumption, which is estimated using USEPA's Vintaging Model for the United States, is used to represent activity data. Consumption is assumed to scale with country gross domestic product (GDP). Regional differences are applied to other developed countries in the European Union

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[2] Abatement options for these types of equipment apply to only those facilities using HFCs. Many such facilities currently use ammonia and hence are not evaluated for further emission reductions in this analysis.

[3] In developing countries, it is assumed that capital costs are 10% higher, fuel prices are 30% higher, electricity costs are 66% higher, and labor costs are 20% lower than those relative to the United States.

(EU) to reflect higher consumption of low-GWP refrigerants in new passenger MVAC systems, domestic refrigerators, and large supermarket systems. For example, HCs have begun to penetrate the EU market in vending machines and other small retail food equipment (e.g., reach-in cases). Adjustments were also made to account for differences in the rates of ODS phaseout relative to the U.S. substitution scenarios.

IV.2.2.2 Emission Estimates and Related Assumptions

Global emissions from refrigeration/AC were estimated at 349 $MtCO_2$ in 2010, projected to grow to 733 $MtCO_2$ by 2020 and 1,596 $MtCO_2$ by 2030. Table 2-1 presents the projected emissions from refrigeration/AC between 2010 and 2030. Growth in emissions is driven largely by GDP. Globally, HFC emissions from refrigeration/AC have been growing also because of the phaseout of ODS under the Montreal Protocol. Growth has also been driven by increased demand for air conditioning equipment, especially in emerging economies. Because of regulations associated with HFC-based refrigerants and/ or growing public pressure to transition away from such refrigerants, many developed countries have transitioned/are transitioning from ODS to natural refrigerants or other low-GWP alternatives in some end-uses. More detail on how HFC consumption and reduction potential of options are modeled is contained in Appendix D to this chapter.

Table 2-1: Projected Baseline Emissions from Refrigeration and AC: 2010 to 2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	45.8	82.7	151.2	328.8	534.1	13.1%
United States	114.0	162.1	213.9	282.5	316.7	5.2%
South Korea	17.0	24.5	35.7	61.1	79.7	8.0%
Russia	16.0	23.2	33.4	56.0	72.0	7.8%
Japan	30.9	38.7	48.0	62.0	66.7	3.9%
Rest of Regions						
Africa	12.5	18.7	28.1	49.3	64.9	8.6%
Central and South America	16.2	23.4	34.3	59.5	78.2	8.2%
Middle East	13.3	19.8	29.6	52.3	69.9	8.6%
Europe	46.3	59.3	74.6	99.9	109.7	4.4%
Eurasia	2.0	2.9	4.2	7.0	9.0	7.9%
Asia	20.6	32.2	52.7	101.3	146.9	10.3%
North America	14.8	20.4	27.4	40.4	48.1	6.1%
World Total	**349.3**	**507.9**	**733.1**	**1,199.9**	**1,596.1**	**7.9%**

[a] CAGR = Compound Annual Growth Rate.

Source: U.S. Environmental Protection Agency (USEPA), 2012.

IV.2.3 Abatement Measures and Engineering Cost Analysis

For the purpose of evaluating the cost of reducing HFC emissions from the refrigeration/AC sector, this analysis considers reduction costs for applying 14 new technologies and using three types of improved technician practices. Table 2-2 summarizes the technology and practice options reviewed and the types of equipment that are assumed to adopt such options, and the associated system type definitions (i.e., the equipment characteristics assumed in order to develop the option costs).

Table 2-2: Refrigeration and AC Abatement Options

Abatement Option	Reduction Efficiency	Applicability
Enhanced HFC-134a in MVACs	50%	New MVACs in light-duty vehicles
HFO-1234yf in MVACs	99.7%	New MVACs in light-duty vehicles
Enhanced HFO-1234yf in MVACs	99.8%	New MVACs in light-duty vehicles
Distributed systems in large retail food	80%	New large retail food refrigeration systems
HFC secondary loop and/or cascade systems in large retail food	94.6%	New large retail food refrigeration systems
NH_3 or HC secondary loop and/or cascade systems in large retail food	100%	New large retail food refrigeration systems
CO_2 Transcritical systems in large retail food	100%	New large retail food refrigeration systems
Retrofits of R-404A systems in large retail food	46%	Existing large retail food refrigeration systems
HCs in small retail food systems	100%	New small retail food refrigeration systems
HC in window units and dehumidifiers	100%	New window AC units and dehumidifiers
R-32 in unitary AC and PTAC/PTHP	75%	New unitary AC equipment and PTAC/PTHP
MCHX in small and medium AC systems	37.5%	New unitary AC equipment
R-32 with MCHX in unitary AC	84.5%	New unitary AC equipment
MCHX in large AC systems	37.5%	New positive displacement chillers
NH_3 or CO_2 in large refrigeration systems	100%	New IPR and cold storage systems
Refrigerant recovery at disposal	85%	All existing refrigeration/AC reaching disposal
Refrigerant recovery at servicing	95%	All small equipment (i.e., MVACs, small unitary AC)
Leak repair	40%	All existing large equipment (i.e., large retail food, IPR, cold storage, and chillers)

A number of these technology options have already begun penetrating certain markets, particularly in the EU, Japan, and several other developed countries. For example, using HCs in small retail food equipment is increasingly common for new equipment sold in the EU and Japanese markets. Likewise, use of alternative refrigerants in passenger MVAC systems has begun in the EU in response to Directive 2006/40/EC (the MAC Directive), which requires replacing HFC-134a with a refrigerant having a GWP of less than 150 in new model vehicles beginning in 2011 and in all new vehicles by 2017.[4] Alternative refrigerants are also increasingly being used in large supermarkets across Northern Europe and to a smaller extent in the United States, Canada, Australia, and other developed countries. The options of increased refrigerant recovery at service and disposal, as well as more rigorous leak repair for large

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[4] Due to supply problems of the refrigerant originally chosen by the MVAC industry (i.e., HFO-1234yf), the EU granted a 2-year dispensation to the auto industry. Additionally, some automobile OEMs have recently announced that they plan to continue to use HFC-134a refrigerant while they further investigate low-GWP options (EurActiv, 2013). Other OEMs have stated that they have not changed their plans to introduce HFO-1234yf and in fact some of these systems are already in operation today (*RAC Magazine*, 2013).

equipment, can bring significant emission savings, especially in developing countries, where they are less likely to be practiced in the baseline.

Each of the abatement options is described further in the sections below. Additional options considered but not yet included in the analysis are described in Sections IV.2.2.18 through IV.2.2.20. Several other options, not mentioned below, are also potentially available but have not been included in this analysis. All costs are presented in 2010 dollars based on the Consumer Price Index (U.S. Department of Labor, 2011).

IV.2.3.1 Enhanced HFC-134a in New MVACs

This option reduces annual leak rates of HFC-134a MVAC systems by 50% through better system components, including improved system sealing, lower permeation hoses, improved fittings, and higher evaporator temperatures (USEPA and NHTSA, 2011). Enhanced HFC-134a systems are additionally assumed to reduce fuel consumption by an estimated 42% through improved component efficiency, improved refrigerant cycle controls, and reduced reheat of the cooled air (USEPA and NHTSA, 2011).

This option is applicable to a newly manufactured MVAC system in light duty vehicles[5] in all countries except the EU, where it is assumed to penetrate in the baseline. The one-time cost is estimated at roughly $73 per MVAC system—assumed to be 10% greater in developing countries. These costs are offset by annual savings that result from reduced fuel and refrigerant consumption (a combined savings of approximately $38 per system). In developing countries, fuel prices are assumed to be 30% greater, resulting in a combined savings of approximately $48 per system.

IV.2.3.2 HFO-1234yf in New MVACs

HFO-1234yf has a GWP of only four and performs similarly to HFC-134a, making the use of current MVAC system designs with minimal changes feasible. HFO-1234yf is, however, slightly flammable (designated 2L flammability in Addendum h to ANSI-ASHRAE Standard 34-2010), which may necessitate certain safety mitigation strategies. This option has already begun penetrating the EU and U.S. markets in a couple models (*Refrigeration and Air Conditioning Magazine*, 2013). This option is assumed to be as efficient as conventional HFC-134a MVAC systems (Oko-Recherche et al., 2011; Koban, 2009).

This option is applicable to a newly manufactured MVAC system in a light-duty vehicle in all countries except the EU, where it is assumed to penetrate the baseline market. The one-time capital cost is estimated at approximately $59 per MVAC system, resulting from incremental refrigerant costs and hardware changes the latter of which is assumed to be 10% greater in developing countries. Annual costs are assumed to be approximately $8 per system associated with incremental refrigerant replacement costs.

IV.2.3.3 Enhanced HFO-1234yf in New MVACs

As a newly developed technology, HFO-1234yf MVAC systems may cost more than those currently containing HFC-134a. Further, a lower global production of the chemical, combined with the additional processes needed to produce it, is expected to lead to an initially high price for the chemical, but this may decrease as production increases. Similar to the Enhanced HFC-134a option, this option explores HFO-

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[5] This category includes cars, pick-up trucks, minivans, and sport utility vehicles.

1234yf for use in new MVAC systems using improved system components to allow for 50% reduced refrigerant leakage and efficiency improvements of 42%.

This option is applied to a newly manufactured MVAC system in light-duty vehicles in all countries. The one-time cost is estimated at roughly $100 per MVAC system, resulting from incremental refrigerant costs and better system components—the latter of which is assumed to be 10% greater in developing countries. The assumed incremental cost of the refrigerant is lower for this option than the original HFO-1234yf option on the basis that, over time with mass production of the chemical and systems to use it, the price will drop. Given this as well as the assumed lower leak rate of this option, annual costs are assumed to be only approximately $2 per MVAC system. These costs are offset by annual savings that result from reduced fuel consumption, equaling roughly $37 per system. In developing countries, fuel prices are assumed to be 30% greater, resulting in a savings of almost $48 per system.

IV.2.3.4 Distributed Systems in New Large Retail Food

A distributed system consists of multiple compressors that are distributed throughout a retail food store (e.g., a supermarket), near the display cases they serve, and are connected by a water loop to a chiller or other type of equipment that rejects heat (e.g., a cooling tower) that is located on the roof or elsewhere outside the store. Because distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional centralized direct expansion (DX) system. The reduction in original charge size of the system will reduce HFC consumption (at first fill) and reduce potential emissions at the end of the equipment’s life. Additionally, because of the placement of the units, a distributed system can require less refrigerant tubing and fittings than DX systems, thereby reducing total HFC leaks during the useful lifetime of the equipment to an estimated 80% relative to conventional systems. However, distributed systems are estimated to be 5% less efficient than conventional HFC centralized DX systems (IPCC, 2005). This technology is already being implemented today in many developed countries.

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. In developed countries, one-time costs are estimated to be 5% more expensive than conventional HFC centralized DX systems (IPCC, 2005), equivalent to an incremental cost of about $9,100 per supermarket; these costs are estimated to be 10% greater in developing countries. Annual costs are estimated at nearly $3,700 per supermarket in developed countries due to higher electricity consumption; these annual electricity costs are estimated to be 66% greater in developing countries. At the same time, annual refrigerant savings (due to reduced leakage) are realized, totaling nearly $1,800 per supermarket.

IV.2.3.5 HFC Secondary Loop and/or Cascade Systems in New Large Retail Food

Secondary loop systems use two fluids: a primary refrigerant and a secondary fluid. The secondary fluid is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment. In supermarkets, secondary loop systems are also sometimes used in combination with a cascade system. Cascade designs consist of two independent refrigeration systems that share a common cascade heat exchanger. The heat exchanger acts as the low temperature refrigerant condenser and serves as the high temperature refrigerant evaporator. Each component of a cascade design uses a different refrigerant that is most suitable for the given temperature range, with CO_2 commonly used in the low temperature circuit and an HFC used as the refrigerant at the medium temperature phase (RTOC, 2011). Because the HFC refrigerant is contained in the machine room in a secondary loop system and is not required for use in the low temperature circuit of a cascade design, these systems require a significantly lower refrigerant charge and have lower leakage rates, resulting in approximately 90% less annual leakage. While historically these systems were less efficient than conventional DX systems, today these systems are found to be just as efficient as conventional DX systems, if not more so, due to simplified piping, newly designed circulating pumps, and fewer components (Wang et al., 2010; DelVentura, et al., 2007; SuperValu, 2012; WalMart, 2006; Hinde, Zha, and Lan, 2009).

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. The one-time cost in developed countries is estimated to be 17.5% more expensive than conventional DX systems (IPCC, 2005), equivalent to an incremental cost of nearly $32,000 per supermarket; this capital cost is estimated to be 10% greater in developing countries. Annual savings associated with reduced refrigerant leakage are estimated to equal almost $2,000 per supermarket. These systems are assumed to be equally as efficient as DX systems, so no costs or savings are associated with annual energy consumption.

IV.2.3.6 NH_3 or HCs Secondary Loop and/or Cascade Systems in New Large Retail Food

Similar to the HFC secondary loop and/or cascade option, in this system a secondary fluid is cooled by a primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment. In some cases, the secondary loop system is also used in combination with a cascade design, which does not rely on any HFCs in the low temperature circuit. For this abatement option, the primary refrigerant is assumed to be ammonia (NH_3) or HCs, which have a GWP that is negligible. Ammonia is not used in conventional supermarket refrigeration systems because such a system could expose consumers to toxic and slightly flammable refrigerant. Similarly, HCs are not used due to their high flammability. However, using a secondary loop allows the primary refrigerant to be isolated to a mechanical room with controlled access to only those with specific training. Because ammonia/HC secondary loop systems avoid running the primary refrigerant through miles of piping to and from food storage cases, they have lower leakage rates than conventional DX systems and operate at reduced charges. In addition, these systems are conservatively assumed to be 5% more energy efficient than conventional DX systems, with some supermarkets reporting actual efficiency gains of 0.5% to 35% (Wang et al., 2010; SuperValu, 2012; Hydrocarbonconversions.com, 2011).

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. The one-time cost in developed countries is estimated to be 25% greater than conventional DX systems (IPCC, 2005), equivalent to an incremental cost of roughly $45,600 per supermarket; this capital cost is estimated to be 10% greater in developing countries. Annual savings are estimated at roughly $5,900 due to both reduced energy consumption and refrigerant savings (due to avoided HFC refrigerant leaks). In developing countries, where electricity rates are assumed to be higher, annual savings are assumed to total more than $8,300.

IV.2.3.7 CO_2 Transcritical Systems in New Large Retail Food

This option eliminates the use of HFCs in large retail food refrigeration systems through the use of CO_2 as the primary refrigerant in a transcritical cycle. CO_2 transcritical systems are similar to traditional centralized DX designs but must operate at high pressures to accommodate the low critical temperature of CO_2 (GTZ Proklima, 2008). As a result, special controls and component specifications must be incorporated into the system design, which often result in higher upfront costs (USEIA, 2012). Additionally, CO_2 transcritical systems operate most efficiently in cooler climates, performing an estimated 5% to 10% more efficiently than DX systems using an HFC refrigerant in regions with an average annual temperature below 50°F (*Supermarket News*, 2012). At the same time, due to a possible energy penalty, the use of CO_2 transcritical systems in warmer climates is currently considered less viable. Specifically, use of these systems is most widely accepted in areas where the maximum ambient temperature is frequently below 88°F (*ACHR News*, 2010), or where the average annual temperature is lower than 59°F (Hill PHOENIX, 2012). Today, it is estimated that over 1,300 CO_2 transcritical systems are currently in operation in Europe with installations as far south as Italy and Spain in addition to a handful of systems that have been installed in Canada (Shecco, 2012). Plans are also currently underway to deploy the technology in supermarkets in the United States.

This abatement option is assumed to be applied to a newly manufactured large retail food system in large supermarkets in cooler climates. One-time costs in developed countries are estimated to be 17.5% more expensive than conventional HFC centralized DX systems (Australian Green Cooling Council, 2008; R744.com, 2012), equivalent to an incremental cost of nearly $32,000 per supermarket; these capital costs are estimated to be 10% greater in developing countries. Annual savings are estimated at about $5,900 per supermarket, which result from both refrigerant savings (due to avoided HFC refrigerant leaks) that total approximately $2,200 per supermarket, and energy savings (due to increased efficiency), which total approximately $3,700 per supermarket. In developing countries, where electricity rates are assumed to be higher, annual savings are assumed to total more than $8,300.

IV.2.3.8 Retrofits of R-404A in Large Retail Food

Retail food refrigeration systems containing R-404A, which have high charge sizes and annual leak rates, can be retrofitted with lower-GWP refrigerants, such as R-407A (with a GWP of 1,770), to reduce their annual climate impact. While some system retrofits will require little to no change to achieve the desired operational characteristics, others may need additional modifications, such as changing the orifice or TXV size to achieve the same efficiency. If proper system evaluation is performed and considerations are taken to ensure the continued reliability of the system, retrofitting can lead to system improvements as a result of recommissioning the equipment (e.g., due to properly setting up controls and system operating valves, which may have wandered from set-point due to lack of maintenance) (*ACHR News*, 2012). However, because such changes may have occurred during remodeling, when the refrigerant retrofit is assumed to occur, no change in energy efficiency due to the new refrigerant is assumed.

To perform a system retrofit, the entire system must be shut down and checks should be made for leaks throughout the system. Solenoid sealings must then be changed as well as the filter driers. After the entire system is evacuated, the replacement fluid is deposited into the system.

For cost modeling purposes, it is assumed that retrofits are performed on large retail food systems at about half-way through its useful lifetime (i.e., 7 years) at the same time retrofits or remodeling of cases are underway. The original R-404A charge size of 1,633 kg is assumed to be replaced with an equivalent amount of R-407A. The procedure is assumed to require 10 hours of a service technician's time (5 hours for the medium temperature system and 5 hours for the low temperature system), all of which is assumed to cost a total of roughly $500 in developed countries and $100 in developing countries (based on technician labor rates). Since the composition of R-404A and R-407A are similar, the cost of the refrigerant is assumed to be the same. Therefore, no annual costs or savings are assumed for this option.

IV.2.3.9 HCs in New Small Retail Food Refrigeration Systems

For small retail food equipment, this option explores the replacement of HFC-134a and R-404A with HCs. HCs, such as butane and propane, have negligible GWPs. Although safety issues associated with HC use in small equipment previously presented a barrier to their use, these issues can be addressed, making them a viable alternative to HFCs. International standards exist to evaluate and mitigate such safety issues. For example, although R-290 (propane) is flammable, it has been successfully implemented in some self-contained hermetic systems.

This option is applied to a newly manufactured small retail food refrigeration system (e.g., stand-alone equipment). No one-time costs are estimated because this option is cost neutral (Unilever, 2008). An annual savings of less than $1 per system is estimated to result from avoided HFC refrigerant costs.

IV.2.3.10 HCs in New Window AC and Dehumidifiers

R-410A is widely used in window AC units and dehumidifiers, brought about by regulations phasing out HCFC-22, which was previously used. By replacing R-410A with HCs, such as propane (R-290), which is assumed to have a negligible GWP, significant emissions can be avoided. Two Chinese AC manufacturers have already commercialized room AC units using R-290. The R-290 AC designs achieve lower refrigerant charge sizes than is currently required by international standard (IEC 60335-2-240) and include additional safety features, such as a special compressor design and refrigerant leak alarm system. Mass production of the R-290 units started in 2009, for initial sale in Europe and China (GTZ-Proklima, 2009).

For cost modeling purposes, this option is applied to newly manufactured window AC units and dehumidifiers. This option is conservatively assumed to have no one-time costs even though there is indication that R-290 AC units can be produced more cheaply than R-410A units as a result of the better heat transfer properties and lower pressure drop of R-290, which allows for the use of narrower tubes in the condenser and evaporator (GTZ-Proklima, 2009). Annual savings are estimated based on the reduced cost of HC refrigerant replacement compared with R-410A—estimated to result in a savings of approximately $0.33 per unit.

IV.2.3.11 R-32 in New Unitary AC Equipment and PTAC/PTHP

In this option, R-32,[6] a mildly flammable (category 2L in ANSI/ASHRAE Standard 34-2010) refrigerant with a GWP of 650, is used in new unitary AC equipment and PTAC/PTHP to replace R-410A, which has a GWP of 1,725. R-32 performs with a reduced charge volume ratio of 66% compared to R-410A (Xu et al., 2012). This reduced charge volume results in a 75% reduction of the direct global warming impact compared to the R-410A system. It is also reportedly 2% to 3% more energy efficient than R-410A (Pham and Sachs, 2010). The equipment used also has the potential to be downsized by up to 15%, which can decrease one-time costs by reducing the amount of materials used. R-32 AC products are already available in Japan and are to be launched in India in February 2013 (Daikin, 2012; Stanga, 2012). Manufacturers in Algeria, China, Thailand, and Indonesia also plan to transition to R-32 AC systems (Stanga, 2012).

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial and large commercial unitary AC) and PTAC/PTHP. The option is conservatively assumed to result in a one-time cost savings of approximately $30 per system, due to the reduced quantity of refrigerant required and lower cost of the alternative refrigerant. Additional savings may be realized through reduced material costs; however, there may also be costs associated with

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[6] R-32 is chosen here due to the availability of data. Other options are under development or being applied. For example, both Godrej in India and Gree in China are producing units with HC refrigerants (Godrej, 2012; Gree, 2012).

designing a system to use a mildly flammable refrigerant. Annual savings are associated with reduced refrigerant replacement costs, estimated at approximately $2.6 per system. Annual energy savings are also likely to be associated with this option but are not quantified in this analysis.

IV.2.3.12 MCHX in New Unitary AC Equipment

This option explores the use of microchannel heat exchangers (MCHX) in unitary AC equipment using R-410A. MCHXs are a modification of conventional heat exchangers, which transfer heat in AC and refrigeration systems (e.g., for the rejection of heat from indoor cooled spaces to the outside ambient space). Because MCHXs transfer heat through a series of small tubes instead of a single or multiple large-diameter tubes, systems using them require between 35% and 40% less refrigerant to operate than those using conventional heat exchangers. Likewise, if average leak rates remain the same,[7] the actual amount of refrigerant emitted would be less. In addition, MCHX systems perform better and are more energy efficient than conventional systems. They also require smaller components, which results in reduced quantities of metals and other materials required per unit, although potential savings in material costs are not analyzed here. MCHXs are already used widely by multiple manufacturers in the automotive industry and in certain models of screw and scroll chillers.

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial, and large commercial unitary AC). One-time savings equal to roughly $27 are assumed due to the smaller refrigerant charge. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $2.30 per system.

IV.2.3.13 R-32 with MCHX in New Unitary AC Equipment

Similar to the option described above, this option explores the use of MCHX in unitary AC equipment but with R-32 refrigerant (with a GWP of 650) in place of R-410A (with a GWP of 1,725). The use of the MCHX results in a refrigerant charge reduction of between 35% and 40% compared with conventional heat exchangers, while the use of R-32 refrigerant allows a further charge size reduction of 66% compared with R-410A. Combined, the reduced charge volume and GWP lead to a lower global warming impact of approximately 85%.

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial, and large commercial unitary AC). One-time savings equal to roughly $46 are assumed as a result of the smaller refrigerant charge and lower cost of the alternative refrigerant. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $3.90 per system.

IV.2.3.14 MCHX in New Positive Displacement Chillers

This option is assumed to be applicable in screw and scroll chillers. As explained above, MCHXs are a modification of conventional heat exchangers, which transfer heat in AC and refrigeration systems (e.g., for the rejection of heat from indoor cooled spaces to the outside ambient space). Because MCHXs transfer heat through a series of small tubes instead of a single or multiple large-diameter tubes, systems

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[7] For example, if average leak rates are dominated by failures or service errors that lead to a catastrophic (100%) loss, and the MCHX system has the same reliability, then average leak rates would be the same.

using them require between 35% and 40% less refrigerant than those using conventional heat exchangers. In addition, MCHX systems perform better and may be more energy efficient than conventional systems. MCHXs are already used widely by multiple manufacturers in the automotive industry and in certain models of screw and scroll chillers.

For cost modeling purposes, this option is applied to a newly manufactured positive displacement chiller. One-time savings equal to nearly $900 are assumed due to the smaller refrigerant charge. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $50 per chiller.

IV.2.3.15 NH_3 or CO_2 in New IPR and Cold Storage Systems

This abatement option is assumed to be applicable to cold storage and industrial process refrigeration systems. Although NH_3 refrigeration systems are already common in refrigerated spaces over 200,000 sq. ft., additional penetration of NH_3 systems is possible in facilities that are less than 200,000 sq. ft. but greater than 50,000 sq. ft. In addition, modern NH_3 absorption refrigeration units are compact, lightweight, efficient, economical, and safe, which has made more applications possible. Improved technologies have also expanded the technical feasibility of using CO_2 systems. CO_2 systems are being used in low-temperature refrigeration (−30°C to −56°C), while ammonia/CO_2 systems can be used for higher temperature refrigeration (−35°C to −54°C). The lower temperature for both systems is limited primarily by the −56°C triple point of CO_2 being used on the low side. The choice between these systems is primarily due to outdoor temperatures; in colder climates, a CO_2 system is both energy efficient and simpler, while in hotter climates a cascade system may be needed to maintain energy efficiency. In Europe and the United States, storage and production facilities have been built with ammonia/CO_2 cascade systems. These systems are estimated to be 2% to 20% more energy efficient compared with their HFC counterparts (Gooseff and Horton, 2008).

For cost modeling purposes, this option is applied to a newly constructed IPR/cold storage refrigeration system/facility. The incremental one-time cost is estimated at approximately $210,700 per system in developed countries (Gooseff and Horton, 2008), assumed to be 10% more in developing countries. The annual savings of approximately $50,300 per system is associated with lower refrigerant replacement costs and reduced energy consumption of 11%; annual electricity cost savings are assumed to be 66% greater for developing countries, resulting in annual savings of approximately $83,100.

IV.2.3.16 Refrigerant Recovery at Disposal for All Existing Equipment Types

Some level of refrigerant recovery at equipment disposal already occurs in the baseline of developed and developing countries, because it is illegal to vent HFCs when equipment is discarded in the U.S. and elsewhere. However, this option explores more widespread, thorough efforts to recover refrigerant at disposal across all equipment types. The approach involves using a refrigerant recovery device that transfers refrigerant into an external storage container prior to disposal of the equipment. Once the recovery process is complete, the refrigerant contained in the storage container may be cleaned by using recycling devices, sent to a reclamation facility to be purified,[8] or destroyed using approved technologies (e.g., incineration).

For cost modeling purposes, this option is applied to an auto dismantling facility assumed to use a single refrigerant recovery device that meets SAE J2788 standards to perform MVAC recovery jobs. The incremental one-time cost is estimated at approximately $2,025 per facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost is estimated to be 10% greater in developing countries. Annual costs are estimated at roughly $1,100 per auto dismantling facility for technician labor time and the purchase of new filters for the recovery device (ICF, 2008). In developing countries, technician labor costs are assumed to be one-fifth the cost of that in developed countries; therefore, annual costs are assumed to be about $240. The annual savings is estimated at about $440 per auto dismantling facility, based on the value of the recovered refrigerant for reclamation/reuse.

IV.2.3.17 Refrigerant Recovery at Servicing for Existing Small Equipment

Similar to disposal recovery, this option assumes more widespread and thorough refrigerant recovery practices while servicing HFC refrigeration/AC systems. Because it is assumed that significant refrigerant is already recovered during servicing of large equipment, this abatement option is only applied to MVAC and small unitary AC systems.

For cost modeling purposes, this option is applied to a U.S. auto servicing facility assumed to perform MVAC servicing jobs using a recovery/recycling (recharge) device designed to meet the SAE J2788 standard. The incremental one-time cost is estimated at approximately $4,050 per servicing facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost is estimated to be 10% greater in developing countries. The annual cost is estimated at roughly $870 per auto servicing facility in developed countries for technician labor time and the purchase of new filters for the recovery device (ICF, 2008); in developing countries, technician labor costs are assumed to be one-fifth the cost of that in developed countries; therefore, the annual cost is assumed to be nearly $194. The annual savings is estimated at roughly $350 per auto servicing facility, based on the value of the recovered refrigerant for reclamation/reuse.

IV.2.3.18 Leak Repair for Existing Large Equipment

This abatement option is assumed to be applicable to large retail food, cold storage and industrial refrigeration, and positive displacement chiller systems. Some level of leak repair activity is already practiced in the baseline, but this option explores additional efforts to repair leaks.

For cost modeling purposes, this option is applied to large supermarkets requiring significant small repairs (e.g., maintenance of the purge system or replacement of a gasket or O-ring). A one-time cost of approximately $1,870 is estimated per supermarket for parts and labor needed to perform the repair in developed countries (USEPA, 1998); in developing countries, this cost is estimated to be 10% greater. The annual savings associated with avoided refrigerant replacement is estimated at $1,470 per supermarket.

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[8] Recycling cleans and reclamation purifies recovered refrigerant; reclamation is more thorough and involves repeated precision distillation, filtering, and contaminant removal. Recycling is used for on-site servicing of MVACs and other equipment, whereas reclamation requires sending the refrigerant off-site to a reclaimer.

IV.2.3.19 HCs in New Domestic Refrigeration Systems

HFC-134a may be replaced with HCs in household refrigerators. HCs, such as butane and propane, have very low GWPs of 4.0 and 3.3, respectively. The main disadvantage of HCs is that they are flammable, but engineering design changes and safety features in manufacturing plants have been successfully implemented to overcome these challenges. In 2009, roughly 40% of new household refrigerators/freezers produced globally contained HCs, with more than 400 million HC units in use worldwide (Greenpeace, 2009). This option is not quantitatively assessed in this analysis but will be considered for future updates.

IV.2.3.20 CO_2 in Transport Refrigeration

CO_2 is currently being used in trucks in cryogenic (open-loop) systems and is also viable for use in refrigerated ships and intermodal containers using a compressor system (Carrier, 2013; Environmental Leader, 2010). However, more sophisticated refrigeration cycles are needed for CO_2 systems to match the efficiency of equivalent HFC units under high ambient temperature operation. The cycle operation is often transcritical, which results in compressor discharge pressures up to five times higher than conventional HFC systems. Therefore, entirely new parts, design approaches, test procedures, service training, etc. are needed to design, build and operate a trans-critical CO_2 system (TEAP, 2011). Due to a lack of readily available cost information on this alternative, this option is not quantitatively assessed in this analysis.

IV.2.3.21 Low-GWP Refrigerants and Blends

Significant research and development (R&D) efforts are underway to identify feasible alternatives for high-GWP HFC refrigerants in multiple subsectors. For instance, the U.S. EPA's Significant New Alternatives Policy (SNAP) program has found - 1233zd(E) (also called trans-1-chloro-3,3,3-trifluoroprop-1-ene) and HFO-1234ze(E) acceptable for use in chillers, used mainly for comfort AC in large residential and commercial buildings, including facilities with data processing and communication centers. Potential alternatives in numerous refrigeration and AC uses include ammonia, hydrocarbons, CO_2, water, HFC-32, and new low-GWP refrigerants such as HFO-1234yf, HFO-1234ze, -1233zd(E), and blends containing HFOs. The Air-Conditioning, Heating and Refrigeration Institute (AHRI) launched the Low-GWP Alternative Refrigerants Evaluation Program to evaluate low-GWP alternatives to HCFC-22, HFC-134a, R-404A, R-407C, and R-410A in various product types (AHRI, 2013). Some 40 chemicals were identified, including refrigerants or blends with no, low, and high flammability. The GWPs of these products also varied, from zero to about 1,300. Some of these blends are under intense development and testing and are most commonly known by trade names, including DR-5, DR-7, DR-33, L-20, L-40, L-41, N-13, N-40, and XP-10. Because of a lack of readily available cost information on this alternative, these options are not quantitatively assessed in this analysis.

IV.2.4 Engineering Cost Data Summary

Table 2-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters.

Table 2-3: Engineering Cost Data on a Facility Basis

Abatement Option/Facility Type	Project Lifetime (years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO$_2$e)[a]
Enhanced HFC-134a					
MVAC—U.S./Other Developed, New	12.0	73.2	37.9	—	0.1
MVAC—EU, New	12.0	73.2	37.9	—	0.1
MVAC—Developing, New	12.0	80.5	48.1	—	0.1
HFO-1234yf					
MVAC—U.S./Other Developed, New	12.0	59.1	—	7.9	0.2
MVAC—EU, New	12.0	59.1	—	7.9	0.2
MVAC—Developing, New	12.0	60.4	—	7.9	0.2
Enhanced HFO-1234yf					
MVAC—U.S./Other Developed, New	12.0	101.7	37.4	2.0	0.2
MVAC—EU, New	12.0	101.7	37.4	2.0	0.2
MVAC—Developing, New	12.0	109.0	47.5	2.0	0.2
Distributed Systems					
Large Retail Food—U.S./Other Developed, New	15.0	9,117.3	1,763.7	3,684.0	656.6
Large Retail Food—EU, New	15.0	9,117.3	1,763.7	3,684.0	656.6
Large Retail Food—Developing, New	15.0	10,029.1	1,763.7	6,139.3	656.6
HFC Secondary Loop and/or Cascade Systems					
Large Retail Food—U.S./Other Developed, New	15.0	31,910.6	1,984.1	—	784.9
Large Retail Food—EU, New	15.0	31,910.6	1,984.1	—	784.9
Large Retail Food—Developing, New	15.0	35,101.7	1,984.1	—	784.9
NH_3 or HC Secondary Loop and/or Cascade Systems					
Large Retail Food—U.S./Other Developed, New	15.0	45,586.6	5,888.6	—	834.0
Large Retail Food—EU, New	15.0	45,586.6	5,888.6	—	834.0
Large Retail Food—Developing, New	15.0	50,145.3	8,343.9	—	834.0
CO_2 Transcritical Systems					
Large Retail Food—U.S./Other Developed, New	15.0	31,910.6	5,888.6	—	834.0
Large Retail Food—EU, New	15.0	31,910.6	5,888.6	—	834.0
Large Retail Food—Developing, New	15.0	35,101.7	8,343.9	—	834.0
Retrofits of R-404A					
Large Retail Food—U.S./Other Developed, Existing	8.0	500.0	—	—	417.1
Large Retail Food—EU, Existing	8.0	500.0	—	—	417.1
Large Retail Food—Developing, Existing	8.0	100.0	—	—	417.1
HCs					
Small Retail Food—U.S./Other Developed, New	20.0	—	0.3	—	0.1
Small Retail Food—EU, New	20.0	—	0.3	—	0.1
Small Retail Food—Developing, New	20.0	—	0.3	—	0.1

(continued)

Table 2-3: Engineering Cost Data on a Facility Basis (continued)

Abatement Option/Facility Type	Project Lifetime (years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)[a]
HCs					
Window Units/Dehumidifiers—U.S./Other Developed, New	11.5	—	0.3	—	0.1
Window Units/Dehumidifiers—EU, New	11.5	—	0.3	—	0.1
Window Units/Dehumidifiers—Developing, New	11.5	—	0.3	—	0.1
R-32					
Unitary AC and PTAC/PTHP—Developed, New	15.0	−29.8	2.6	—	1.2
Unitary AC and PTAC/PTHP—Developing, New	15.0	−29.8	2.6	—	1.2
MCHX					
Unitary AC—Developed, New	15.0	−27.0	2.3	—	0.8
Unitary AC—Developing, New	15.0	−27.0	2.3	—	0.8
R-32 with MCHX					
Unitary AC—Developed, New	15.0	−45.7	3.9	—	1.3
Unitary AC—Developing, New	15.0	−45.7	3.9	—	1.3
MCHX					
Positive Displacement Chiller—Developed, New	20.0	−877.5	52.7	—	11.3
Positive Displacement Chiller—Developing, New	20.0	−877.5	52.7	—	11.3
NH_3 or CO_2					
IPR/Cold Storage—Developed, New	25.0	210,659.6	50,228.1	—	258.8
IPR/Cold Storage—Developing, New	25.0	231,725.6	83,121.0	—	258.8
Recovery at Disposal					
Auto Disposal Yard—U.S./Other Developed	7.0	2,025.6	443.3	1,083.8	72.0
Auto Disposal Yard—EU	7.0	2,025.6	443.3	1,083.8	72.0
Auto Disposal Yard—Developing	7.0	2,228.1	443.3	237.0	72.0
Recovery at Servicing					
Auto servicing station—U.S./Other Developed	7.0	4,051.1	351.1	869.5	57.1
Auto servicing station—EU	7.0	4,051.1	351.1	869.5	57.1
Auto servicing station—Developing	7.0	4,456.3	351.1	194.2	57.1
Leak Repair					
Large Retail Food—U.S./Other Developed, Existing	5.0	1,872.9	1,469.7	—	532.4
Large Retail Food—EU, Existing	5.0	1,872.9	1,469.7	—	532.4
Large Retail Food—Developing, Existing	5.0	2,060.2	1,469.7	—	532.4

[a] Emission reductions shown include only reductions associated with HFCs; they do not include indirect (CO_2) emissions associated with differences in energy consumption.

IV.2.5 Marginal Abatement Costs Analysis

This section describes the methodological approach to the assessment of international abatement measures for refrigeration and air conditioning.

IV.2.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities in the United States, developed countries, and developing countries. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline (that is, the HFC emissions from the traditional ODS industries) attributable to each representative type of equipment and the technical effectiveness for each technology in each facility or system.

IV.2.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/region/equipment type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by facility in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time as systems are upgraded; market penetration is a modeled value that accounts for a number of elements, such as market choice, the turnover rate to replace existing banks of equipment that use HFCs, and the lifetime of refrigeration and air-conditioning equipment. Technical effectiveness figures do not account for indirect GHG impacts (i.e., increases or decreases in electricity or fuel consumption), which are accounted for in the cost analysis.[9] Table 2-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

Table 2-4: Technical Effectiveness Summary

Facility/Abatement Option	Technical Applicability	Market Penetration Rate (2030)[a]	Reduction Efficiency	Technical Effectiveness (2030)[b]
MVACs – U.S./Other Developed				
Enhanced HFC-134a	New systems	0%	50%	0%
HFO-1234yf		0%	99.7%	36%
Enhanced HFO-1234yf		100%	99.8%	64%
MVACs – EU				
Enhanced HFC-134a	New systems	0%	50%	0%
HFO-1234yf		0%	99.7%	0%
Enhanced HFO-1234yf		100%	99.8%	32%

(continued)

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[9] Indirect GHG emissions are not accounted for in the technical effectiveness calculations so that the analysis can show purely ODS substitute (e.g., HFC) emission reductions achievable. While it is recognized that indirect GHG emissions can be significant, the incremental differences of the options considered here compared to traditional HFC systems are expected to be relatively small. Such differences, to the extent data is available on such, are accounted for in the cost analyses.

Table 2-4: Technical Effectiveness Summary (continued)

Facility/Abatement Option	Technical Applicability	Market Penetration Rate (2030)[a]	Reduction Efficiency	Technical Effectiveness (2030)[b]
MVACs –Developing				
Enhanced HFC-134a	New systems	0%	50%	4%
HFO-1234yf		100%	99.7%	44%
Enhanced HFO-1234yf		0%	99.8%	0%
Large Retail Food – U.S./Other Developed				
Distributed systems	New systems	10%	80%	17%
HFC secondary loop and/or cascade systems		50%	95%	28%
NH_3 or HC secondary loop and/or cascade systems		20%	100%	13%
CO_2 transcritical systems		20%	100%	19%
Retrofits of R-404A	R-404A systems at or beyond average age	100%	46%	1%
Large Retail Food – EU				
Distributed systems	New systems	0%	80%	10%
HFC secondary loop and/or cascade systems		0%	95%	16%
NH_3 or HC secondary loop and/or cascade systems		35%	100%	21%
CO_2 transcritical systems		60%	100%	47%
Retrofits of R-404A	R-404A systems at or beyond average age	100%	46%	1%
Large Retail Food – Developing				
Distributed systems	New systems	30%	80%	15%
HFC secondary loop and/or cascade systems		37%	95%	16%
NH_3 or HC secondary loop and/or cascade systems		13%	100%	4%
CO_2 transcritical systems		20%	100%	8%
Retrofits of R-404A	R-404A systems at or beyond average age	100%	46%	3%
Small Retail Food – U.S./Other Developed				
HCs	New systems	100%	100%	68%
Small Retail Food – EU				
HCs	New systems	100%	100%	62%
Small Retail Food – Developing				
HCs	New systems	100%	100%	27%
Window AC Units and Dehumidifiers – U.S./Other Developed				
HCs	New systems	34%	100%	3%
Window AC Units and Dehumidifiers – EU				
HCs	New systems	50%	100%	3%

(continued)

Table 2-4: Technical Effectiveness Summary (continued)

Facility/Abatement Option	Technical Applicability	Market Penetration Rate (2030)[a]	Reduction Efficiency	Technical Effectiveness (2030)[b]
Window AC Units and Dehumidifiers – Developing				
HCs	New systems	50%	100%	3%
PTAC/PTHP - Developed				
R-32	New systems	100%	75%	22%
PTAC/PTHP – Developing				
R-32	New systems	50%	75%	6%
Unitary AC – Developed				
R-32	New systems	0%	75%	27%
MCHX		0%	37.5%	11%
R-32 with MCHX		100%	84.5%	23%
Unitary AC – Developing				
R-32	New systems	50%	75%	8%
MCHX		50%	37.5%	12%
R-32 with MCHX		0%	84.5%	0%
Large AC: PD Chillers – Developed				
MCHX	New systems	100%	37.5%	20%
Large AC: PD Chillers – Developing				
MCHX	New systems	100%	37.5%	19%
IPR & Cold Storage – Developed				
NH_3 or CO_2	New systems	40%	100%	21%
IPR & Cold Storage – Developing				
NH_3 or CO_2	New systems	20%	100%	5%
Cross-Cutting Practice Options – U.S/Other Developed				
Refrigerant recovery at disposal	Existing equipment	100%	85%	39%
Refrigerant recovery at servicing (small equipment)		40%	95%	16%
Leak repair (large equipment)		100%	40%	64%
Cross-Cutting Practice Options – EU				
Refrigerant recovery at disposal	Existing equipment	100%	85%	65%
Refrigerant recovery at servicing (small equipment)		40%	95%	15%
Leak repair (large equipment)		100%	40%	84%
Cross-Cutting Practice Options – Developing				
Refrigerant recovery at disposal	Existing equipment	100%	85%	35%
Refrigerant recovery at servicing (small equipment)		40%	95%	20%
Leak repair (large equipment)		100%	40%	42%

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in Appendix D to this chapter.

[b] Technical effectiveness figures represent the percentage of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts (i.e., increases or decreases in electricity or fuel consumption), which are accounted for in the cost analysis.

IV.2.5.3 Estimating Abatement Project Costs and Benefits

Table 2-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for developed and developing countries. Additional details on the analyses can be found in Appendix D to this chapter.

Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC

Abatement Option/Facility Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Enhanced HFC-134a					
MVAC—U.S./Other Developed, New	0.1	198.7	−420.8	45.1	−267.2
MVAC—EU, New	0.1	198.7	−420.8	45.1	−267.2
MVAC—Developing, New	0.1	218.6	−533.8	49.6	−364.8
HFO-1234yf					
MVAC—U.S./Other Developed, New	0.2	67.3	36.8	15.3	88.8
MVAC—EU, New	0.2	67.3	36.8	15.3	88.8
MVAC—Developing, New	0.2	68.7	36.8	15.6	89.9
Enhanced HFO-1234yf					
MVAC—U.S./Other Developed, New	0.2	115.5	−164.2	26.2	−74.9
MVAC—EU, New	0.2	115.5	−164.2	26.2	−74.9
MVAC—Developing, New	0.2	123.9	−211.5	28.1	−115.8
Distributed systems					
Large Retail Food—U.S./Other Developed, New	656.6	3.0	2.9	0.6	5.4
Large Retail Food—EU, New	656.6	3.0	2.9	0.6	5.4
Large Retail Food—Developing, New	656.6	3.3	6.7	0.7	9.3
HFC secondary loop and/or cascade systems					
Large Retail Food—U.S./Other Developed, New	784.9	8.9	−2.5	1.8	4.6
Large Retail Food—EU, New	784.9	8.9	−2.5	1.8	4.6
Large Retail Food—Developing, New	784.9	9.8	−2.5	2.0	5.3
NH_3 or HC secondary loop and/or cascade systems					
Large Retail Food—U.S./Other Developed, New	834.0	12.0	−7.1	2.4	2.5
Large Retail Food—EU, New	834.0	12.0	−7.1	2.4	2.5
Large Retail Food—Developing, New	834.0	13.2	−10.0	2.7	0.5
CO_2 Transcritical systems					
Large Retail Food—U.S./Other Developed, New	834.0	8.4	−7.1	1.7	−0.4
Large Retail Food—EU, New	834.0	8.4	−7.1	1.7	−0.4
Large Retail Food—Developing, New	834.0	9.2	−10.0	1.9	−2.7

(continued)

Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC (continued)

Abatement Option/Facility Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Retrofits of R-404A					
Large Retail Food—U.S./Other Developed, Existing	417.1	0.4	—	0.1	0.3
Large Retail Food—EU, Existing	417.1	0.4	—	0.1	0.3
Large Retail Food—Developing, Existing	417.1	0.1	—	0.0	0.1
HCs					
Small Retail Food—U.S./Other Developed, New	0.1	—	−3.5	—	−3.5
Small Retail Food—EU, New	0.1	—	−3.5	—	−3.5
Small Retail Food—Developing, New	0.1	—	−3.5	—	−3.5
HCs					
Window Units/Dehumidifiers—U.S./Other Developed, New	0.1	—	−2.6	—	−2.6
Window Units/Dehumidifiers—EU, New	0.1	—	−2.6	—	−2.6
Window Units/ Dehumidifiers—Developing, New	0.1	—	−2.6	—	−2.6
R-32					
Unitary AC and PTAC/PTHP—Developed, New	1.2	−5.6	−2.2	−1.1	−6.7
Unitary AC and PTAC/PTHP—Developing, New	1.2	−5.6	−2.2	−1.1	−6.7
MCHX					
Unitary AC—Developed, New	0.8	−7.3	−2.9	−1.5	−8.7
Unitary AC—Developing, New	0.8	−7.3	−2.9	−1.5	−8.7
R-410A to R-32					
Unitary AC—Developed	1.2	−5.6	−2.2	−1.1	−6.7
Unitary AC—Developing	1.2	−5.6	−2.2	−1.1	−6.7
R-32 with MCHX					
Unitary AC—Developed	1.3	−7.6	−3.0	−1.5	−9.1
Unitary AC—Developing	1.3	−7.6	−3.0	−1.5	−9.1
MCHX					
Positive Displacement Chiller—Developed, New	258.8	149.5	−194.1	21.7	−66.3
Positive Displacement Chiller—Developing, New	258.8	164.4	−321.2	23.9	−180.7
NH_3 or CO_2					
IPR/Cold Storage—Developed, New	258.8	149.5	−194.1	21.7	−66.3
IPR/Cold Storage—Developing, New	258.8	164.4	−321.2	23.9	−180.7
Recovery at disposal					
Auto Disposal Yard—U.S./Other Developed	72.0	9.6	8.9	2.7	15.8
Auto Disposal Yard—EU	72.0	9.6	8.9	2.7	15.8
Auto Disposal Yard—Developing	72.0	10.6	−2.9	2.9	4.8

(continued)

Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC (continued)

Abatement Option/Facility Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/\text{tCO}_2\text{e}$)	Net Annual Cost ($\$/\text{tCO}_2\text{e}$)	Tax Benefit of Depreciation ($\$/\text{tCO}_2\text{e}$)	Break Even Price ($\$/\text{tCO}_2\text{e}$)
Recovery at servicing					
Auto servicing station—U.S./Other Developed	57.1	24.3	9.1	6.8	26.6
Auto servicing station—EU	57.1	24.3	9.1	6.8	26.6
Auto servicing station—Developing	57.1	26.7	−2.8	7.4	16.5
Leak Repair					
Large Retail Food—U.S./Other Developed, Existing	532.4	1.5	−2.8	0.5	−1.7
Large Retail Food—EU, Existing	532.4	1.5	−2.8	0.5	−1.7
Large Retail Food—Developing, Existing	532.4	1.7	−2.8	0.5	−1.6

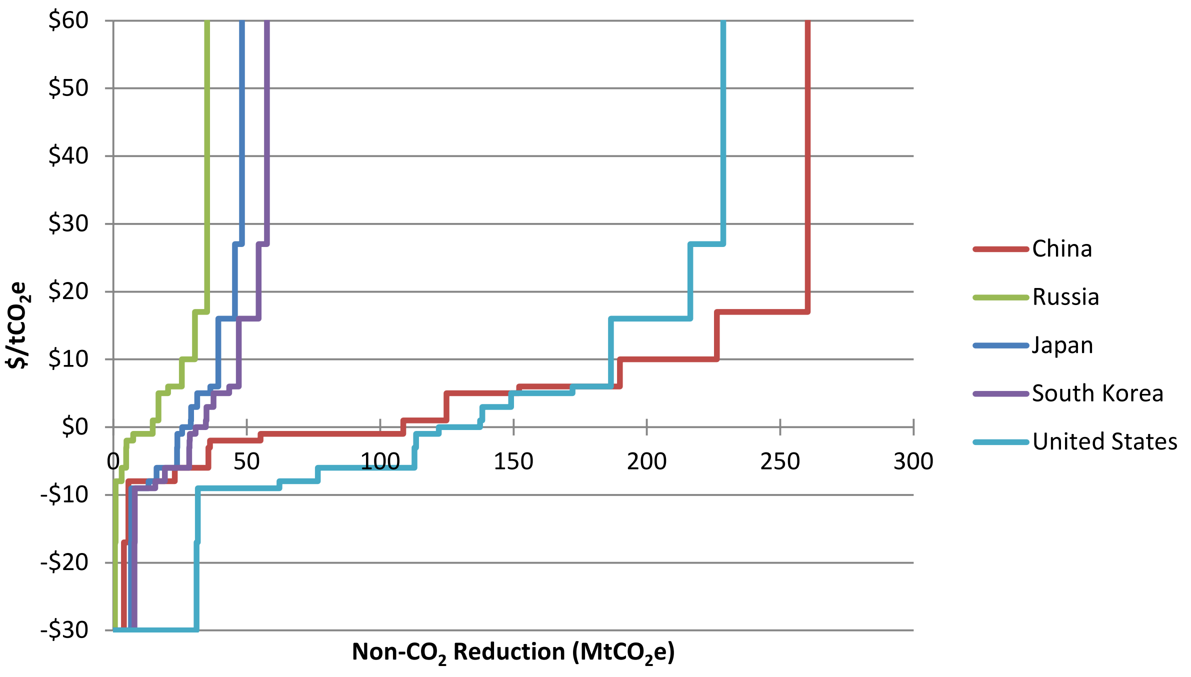
IV.2.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 208 and 994 MtCO$_2$e, respectively. There are 479 MtCO$_2$e of emissions reductions available in 2030 from implementing currently available technologies that are cost-effective at projected costs. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to users or manufacturers of refrigeration and AC systems, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 2-6 and Figure 2-4 by major country and regional grouping at select break-even prices in 2030.

Table 2-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 (MtCO$_2$e)

	Break-Even Price ($\$/\text{tCO}_2\text{e}$)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
China	5.6	35.6	108.7	152.1	226.2	226.2	260.4	260.4	260.4	279.1	279.1
Japan	6.7	23.8	29.0	36.3	39.3	39.3	45.6	48.2	48.2	51.2	51.2
Russia	0.8	4.8	14.7	20.5	30.5	30.5	35.1	35.1	35.1	37.6	37.6
South Korea	8.0	28.4	34.6	43.3	47.0	47.0	54.5	57.6	57.6	61.2	61.2
United States	31.7	112.9	137.5	172.1	186.5	186.5	216.3	228.6	228.6	243.1	243.1
Rest of Region											
Africa	0.7	4.3	13.2	18.5	27.5	27.5	31.6	31.6	31.6	33.9	33.9
Central and South America	1.0	5.9	16.5	22.9	33.5	33.5	38.6	38.7	38.7	41.5	41.5
Middle East	2.9	11.8	19.9	26.3	33.7	33.7	38.9	39.9	39.9	42.6	42.6
Europe	2.8	29.8	49.2	62.0	66.0	66.0	78.6	82.1	82.1	82.7	82.7
Eurasia	0.1	0.6	1.8	2.6	3.8	3.8	4.4	4.4	4.4	4.7	4.7
Asia	2.6	13.4	32.7	45.0	64.2	64.2	74.0	74.5	74.5	79.8	79.8
North America	4.8	17.2	20.9	26.2	28.4	28.4	32.9	34.8	34.8	37.0	37.0
Total	**67.7**	**288.4**	**478.6**	**627.7**	**786.7**	**786.7**	**910.9**	**935.8**	**935.8**	**994.3**	**994.3**

Figure 2-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



IV.2.6 Uncertainties and Limitations

The development of alternative refrigerants and technologies is quickly evolving in this sector, with efficiencies increasing and costs decreasing as research and market share expand. Thus, the costs and reduction efficiencies of the alternatives reviewed in this analysis are subject to change and likely very conservative. Moreover, new options not quantified in this analysis are entering the market and will continue to do so; additional options, such as HCs in domestic refrigerators, CO_2 in transport refrigeration, and low-GWP refrigerants for comfort cooling chillers, could be quantitatively considered in future analyses.

In addition, the costs for the options explored in this analysis are highly variable, depending on the types of systems reviewed. In particular, estimates of the amount of refrigerant recoverable from equipment at service and disposal are highly uncertain and highly variable based on the type of equipment. Recovery from large equipment is generally more cost-effective than for small equipment, because the amount of refrigerant recoverable is greater and the relative amount of technician time needed to perform the recovery is smaller. Similarly, because leak repair can be performed on many different equipment types and can involve many different activities/tools, it is difficult to determine an average cost of such repairs or the average emission reduction associated with them. This analysis, therefore, relies on broad assumptions available in the published literature, which may not reflect specific or even average values for the leak repair activities modeled.

Finally, it is assumed that numerous abatement options result in increased or decreased energy consumption (e.g., enhanced HFO-1234yf or HFC-134a in MVACs, CO_2 transcritical large retail food refrigeration systems, distributed refrigeration systems, NH_3 or CO_2 in new IPR and cold storage systems). While the costs associated with the increase or decrease in energy consumption, which would vary widely based on region as well as particular application, is quantified as part of this analysis, the increase or decrease in CO_2 emissions associated with this energy use is not quantified. To accurately capture net emission reductions of these abatement options, emissions associated with the increase or decrease in energy use should also be calculated.

References

3M. 2008. Personal communication between John Owens of 3M and Emily Herzog of ICF International. August 2008.

Air-Conditioning, Heating and Refrigeration Institute (AHRI). 2013. AHRI Low-GWP Alternative Refrigerants Evaluation Program. Available at http://www.ahrinet.org/ahri+low_gwp+alternative+refrigerants+evaluation+program.aspx. Accessed August 28, 2013.

Air Conditioning, Heating, Refrigeration News (ACHR News). 2012. Retrofitting with HCFs. December 3, 2012. Available at: http://digital.bnpmedia.com/publication/?i=136503.

Air Conditioning, Heating, Refrigeration News (ACHR News). 2010. CO_2 in Supermarket Refrigeration. September 6, 2010. Available at: http://www.achrnews.com/articles/co2-in-supermarket-refrigeration.

Arthur D. Little, Inc. (ADL). 2002. *Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant, and Fire Protection Applications*. Final Report to the Alliance for Responsible Atmospheric Policy. Reference Number 75966.

Automotive Engineering International (AEI). 2008. "Consensus Building on Refrigerant Type." September 2008.

Australian Green Cooling Council. 2008. Transcritical CO_2 (R744) Supermarket Refrigeration in Australia. Available at: http://ec.europa.eu/clima/events/0007/australian_green_cooling_en.pdf.

Carrier. November 11, 2008. Personal communication between William Walter and Richard Lord of Carrier, and Brie Johnson of ICF International.

Carrier. 2013. NaturaLINE: Another Milestone in Innovation and Sustainability. Obtained June 12, 2013, at: http://www.container.carrier.com/Carrier+Brand+Sites/Carrier+Transicold+Container/Side+Bar+Links/Home/NaturaLINE.

Centro Ricerche Fiat. June 10, 2008. *The Four Fiat Pandas Experiment - To evaluate different MAC systems.* Presentation given by C-Aa Malvicino, Head of Thermal Systems Dept., Centro Ricerche Fiat at the SAE 2008 Alternate Refrigerant Systems Symposium, Scottsdale, AZ.

Daikin. September 27, 2012. *News Release: World's First Commercialization of Air Conditioning Equipment Using Next-Generation Refrigerant HFC32*. Obtained February 14, 2013, at: http://www.daikin.com/press/2012/120927/index.html.

DelVentura, R. et al., September 2007. "BOHN the Cold Standard: Secondary Loop Systems for the Supermarket Industry." White Paper.

Koban, Mary (DuPont Fluoroproducts). 2009. "HFO-1234yf Low GWP Refrigerant LCCP Analysis." Presented at SAE 2009 World Congress. April 2009.

Earthcare. October 2008. Personal communication between Nicholas Cox, Earthcare Products Ltd., and Brie Johnson, ICF International.

Environmental Investigation Agency. 2012. *HFC-Free Technologies Are Available in the US Market for the Supermarket-Retail Refrigeration Sector.* Available at http://eia-global.org/PDF/USSUPERMARKETREPORT.pdf.

Environmental Leader: Environmental and Energy Management News. December 1, 2010. "Carrier Unveils Natural Refrigerated Transport Solution." Obtained January 25, 2013, at: http://www.environmentalleader.com/2010/12/01/carrier-unveils-natural-refrigerated-transport-solution/.

EurActiv. January 23, 2013. "Daimler Faces Legal Action Threat over Green Air Conditioning." Obtained February 7, 2013, at: http://www.euractiv.com/climate-environment/daimler-slammed-return-mac-direc-news-516741.

Godrej. 2012. "HC Technology for Room Air Conditioners." Presented by Dilip Rajadhyaksha at Advancing Ozone and Climate Protection Technologies: Next Steps, Bangkok, Thailand. July 21-22, 2012.

Gooseff, A., and J. Horton. 2008. "Ammonia as the Sustainable Refrigerant: An Ammonia-Halocarbon Comparison." Presented at 30th Annual Meeting International Institute of Ammonia Refrigeration, Colorado Springs, CO. March 16-19, 2008.

Gree Electronic Appliances. 2012. "Application of HC Refrigerant in Room Air Conditioners." Presented at Advancing Ozone and Climate Protection Technologies: Next Steps, Bangkok, Thailand. July 21-22, 2012.

Greenpeace. 2009. *Cool Technologies: Working Without HFCs: Examples of HFC-Free Cooling Technologies in Various Industrial Sectors*. Prepared by J. Maté of Greenpeace International with C. Papathanasopoulos of Greenpeace USA. Available at: http://www.greenpeace.org/usa/assets/binaries/cool-technology-report-2009.

GTZ Proklima. 2008. *Natural Refrigerants: Sustainable Ozone- and Climate-Friendly Alternatives to HCFCs*. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Eschborn, Germany. July 2008. Available at: http://epa.gov/greenchill/downloads/en-gtz-proklima-natural-refrigerants.pdf.

GTZ Proklima. 2009. Gree Electric R290 Air Conditioner. Presented on behalf of Gree by Dr. Volkmar Hasse, GTZ-Proklima International, at the Joint West Asia and South Asia Network Meeting. May 10, 2009. Available at: http://www.hydrocarbons21.com/files/news/gree-ac-unit-hydrocarbons.pdf.

Hill PHOENIX. 2012. "Advances in CO_2 Supermarket Refrigeration in North America." Presented by S. Martin, Hill PHOENIX, at the ATMOsphere 2012 conference, Washington, DC. Available at: http://www.atmo.org/media.presentation.php?id=139.

Hinde, D. Zha, S. and Lan, L ASHRAE. February 2009. "Carbon Dioxide in North American Supermarkets." *ASHRAE Journal* 51.

Hydrocarbonconversions.com. November 15, 2011. *200 Lidl stores to feature R290 technology by 2012*. Available at: http://www.hydrocarbonconversions.com/200-lidl-stores-to-feature-r290-technology-by-2012/.

ICF International. 2008. *Regulatory Impact Analysis (RIA) of Current Section 609 Requirements and Potential Updates: Draft Report*. Submitted to the U.S. EPA. Washington, DC: ICF International.

Intergovernmental Panel on Climate Change (IPCC). 2005. *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons.* In B. Metz, L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, et al. (Eds.). Prepared by Working Groups I and III of the IPCC, and the Technical and Economic Assessment Panel. New York, NY: Cambridge University Press.

Oko-Recherche, Oko-Institute, HEAT International, Danish Technological Institute, Re-phridge, Karlsruhe University of Applied Sciences, Estonia Environmental Research Centre, and Ammonia Partnership. 2011. *Preparatory study for a review of regulation (EC) No 842/2006 on certain fluorinated greenhouse gases.* Prepared for the European Commission. September 2011.

Pham, H. and H. Sachs. 2010. *Next Generation Refrigerants: Standards and Climate Policy Implications of Engineering Constraints.* ACEEE Summer Study on Energy Efficiency in Buildings. Available at: http://www.aceee.org/files/proceedings/2010/data/papers/1933.pdf.

R744.com. 2012. *Cascade CO2 could be winning option in emerging economies - CCAC Forum, Part I18*. December 18, 2012. Available at http://www.r744.com/news/view/3755.

Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC). 2011. *2010 Assessment.* UNEP Nairobi. Available at: http://ozone.unep.org/teap/Reports/RTOC/RTOC-Assessment-report-2010.pdf.

Refrigeration and Air Conditioning (RAC) Magazine. 2013. "US car giant GM publicly backs HFO-1234yf." January 7, 2013. Obtained February 7, 2013, at: http://www.racplus.com/news/us-car-giant-gm-publicly-backs-1234yf/8640815.article?blocktitle=Latest-news&contentID=2332.

Rugh, J., and V. Hovland. July 17, 2003. National and World Fuel Savings and carbon dioxide Emission Reductions by Increasing Vehicle Air Conditioning COP. Presented by John Rugh and Valerie Hovland of the National Renewable Energy Laboratory at the SAE 2003 Automotive Alternate Refrigerant Systems Symposium in Phoenix, AZ. Society of Automotive Engineers.

Shecco. 2012. "2012: Natural Refrigerants Market Growth for Europe." Available at: http://guide.shecco.com/.

Stanga, M. December 13, 2012. *Correspondence: Cost of R-32 for unitary AC equipment.*

Supermarket News. 2012. "Refrigeration Systems Chillin' with Carbon Dioxide." Available at: http://supermarketnews.com/technology/refrigeration-systems-chillin-carbon-dioxide?page=1showtext.cfm?t=ptb0810.

SuperValu. June 12, 2012. *SuperValu's Development of Next Generation Refrigeration Systems: Application of Ammonia, CO_2 and Propane*. Heath, R. and J. Armer. Presented at ATMOsphere America the Business Case: Natural Refrigerants.

Technology and Economic Assessment Panel (TEAP). 2012. *Decision XXIII/9 Task Force Report: Additional Information on Alternatives to Ozone-Depleting Substances*.

Technology and Economic Assessment Panel (TEAP). 2011. *UNEP 2010 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee: 2010 Assessment*. February 2011. ISBN 978-9966-20-002-0. Available at http://ozone.unep.org/teap/Reports/RTOC/RTOC-Assessment-report-2010.pdf.

Unilever. 2008. "Unilever Ice Cream Cabinets: Conversion to Natural Refrigerants." Case Study disseminated at the EC International Technical Meeting on HCFC Phase-Out. Montreal, Canada, April 5–6, 2008. Available at: http://ec.europa.eu/environment/ozone/pdf/unilever_hfc_icecream_cabinets.pdf.

U.S. Bureau of Labor Statistics (BLS). 2007. Occupational Employment and Wages, May 2006: 49-3023 Automotive Service Technicians and Mechanics. Available at: http://www.bls.gov/oes/current/oes493023.htm.

U.S. Bureau of Labor Statistics (BLS). 2011. Consumer Price Index. Obtained May 2011 at: http://www.bls.gov/cpi/.

U.S. Energy Information Administration (USEIA). 2011. Annual Energy Review: 2010 industrial (real) Electricity Cost. Table 8.10: Average Retail Prices of Electricity, 1960-2010. Available at http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0810. Accessed October 19, 2011.

U.S. Energy Information Administration (USEIA). 2008. Retail Motor Gasoline Prices in Selected Countries, 1990-2007. Obtained October 2008, at: http://www.eia.gov/countries/prices/gasolinewithtax.cfm.

U.S. Environmental Protection Agency (USEPA). May 1998. *Draft Regulatory Impact Analysis: The Substitutes Recycling Rule*. Prepared by ICF Incorporated for U.S. Environmental Protection Agency. Washington, DC: ICF International.

U.S. Environmental Protection Agency (USEPA). June 2001. *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions*. EPA #000-F-97-000. Washington, DC: Office of Air and Radiation, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). June 2006. *Global Mitigation of Non-CO_2 Greenhouse Gases.* EPA #430-R-06-005. Washington, DC: Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). October 2009. *Marginal Abatement Cost Curve Analysis for Reduction of HFCs in Traditional Ozone Depleting Substance (ODS) End-Use Applications: Draft Report*. Prepared by ICF International for U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). (2012a). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency and National Highway Traffic Safety Administration (USEPA and NHTSA). 2011. *Draft Joint Technical Support Document: Proposed Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards.*

WalMart. September 2006. *DOW Case Study: Secondary Loop Refrigeration and DOWFROST^{TM} Fluid Contribute to Wal-Mart "Green Initiative."*

Wang, K., M. Eisele, Y. Hwang, and R. Radermacher. October 2010. Review of secondary loop refrigeration systems. *International Journal of Refrigeration* 33 (2), 212–234.

Xu, X., Y. Hwang, and R. Radermacher. 2012. "Performance Measurement of R32 in Vapor Injection Heat Pump System." Presented at the International Refrigeration and Air Conditioning Conference at Purdue, July 16–19, 2012.

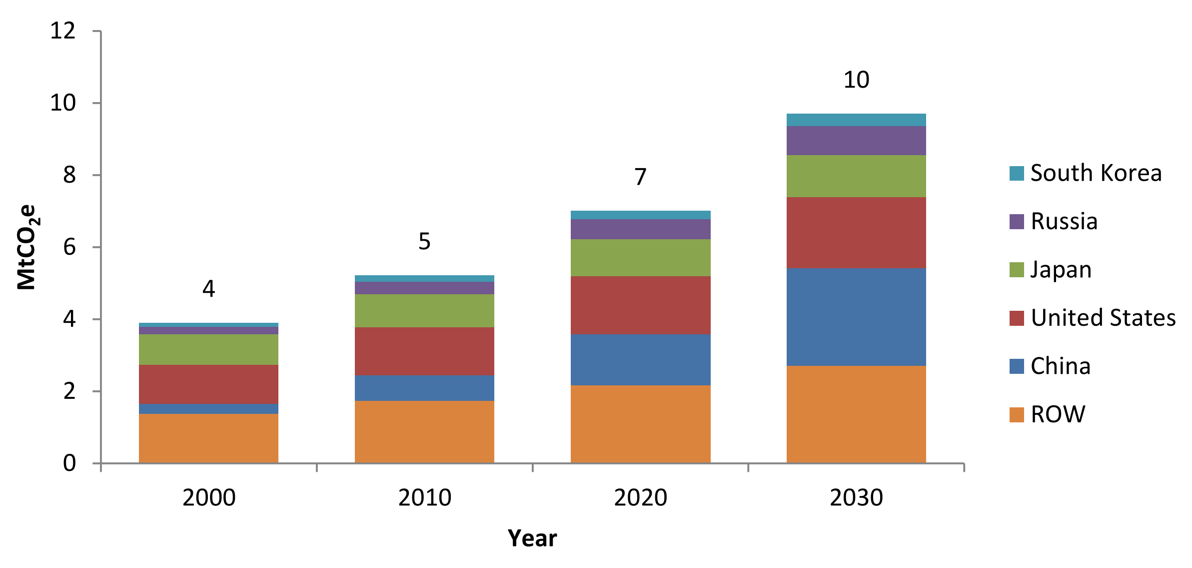
IV.3. HFC Emissions from Solvent Use

IV.3.1 Sector Summary

Historically, chlorofluorocarbons (CFCs) (in particular CFC-113), methyl chloroform, and, to a lesser extent, carbon tetrachloride were used as the predominant solvent cleaning agents. Hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), perfluorocarbons (PFCs), and aqueous and semi-aqueous not-in-kind (NIK) solvents have since replaced these historical solvents, with HFC emissions currently dominating the global warming potential (GWP)-weighted emissions from the solvents sector.

Greenhouse gas emissions from the solvents sector (excluding CFCs and HCFCs) were estimated at roughly 5 million metric tons of carbon dioxide equivalent ($MtCO_2e$.) in 2010. By 2030, emissions from this sector are expected to more than double, reaching over 10 $MtCO_2e$. A majority of the growth will result from increased use of HFCs in developing countries. Figure 3-1 presents the HFC and PFC baseline emissions from solvent use between 2000 and 2030.

Figure 3-1: HFC and PFC Emissions from Solvent Use: 2000–2030 ($MtCO_2e$)



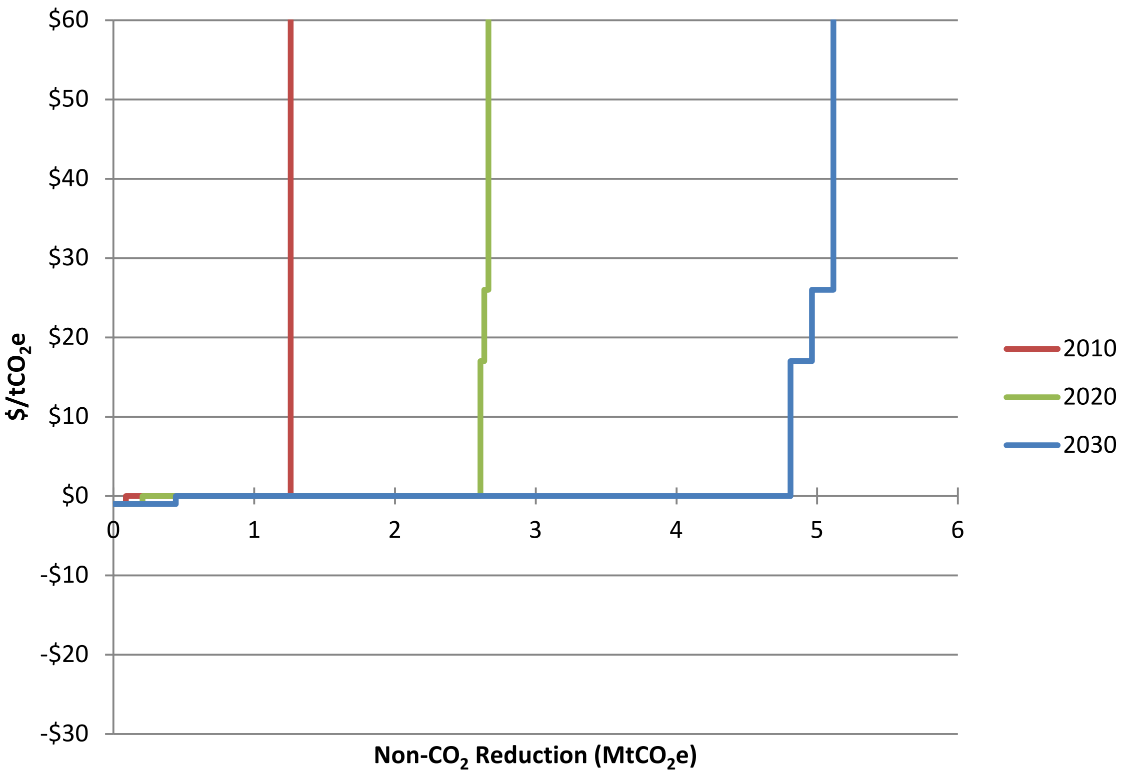
Source: U.S. Environmental Protection Agency (USEPA), 2012a

Four abatement options were identified for the solvent sector: (1) replacement of HFCs with HFEs, (2) retrofitting of equipment, (3) transition to NIK aqueous, and (4) transition to NIK semi-aqueous.

The global abatement potential is equal to approximately 58.9% of total annual emissions from the solvent sector and 0.3% of total annual emissions from all sectors that use ODS substitutes. These results are partly due to the assumed adoption of HFEs which, although they have a relatively lower GWP than HFCs, still result in emissions of greenhouse gases. In the same way, the adoption of equipment retrofits, another abatement option, still results in emissions of greenhouse gases. Finally, it is assumed that due to the performance limitations of the available alternatives, in the absence of policy measures, a portion of the market will not make the transition away from HFCs.

Marginal abatement cost (MAC) curve results are presented in Figure 3-2. Maximum abatement potential in the solvents sector is 5.7 $MtCO_2e$ in 2030. There are 4.8 $MtCO_2e$ of emissions reductions in 2030 that are cost-effective (i.e., $0/$tCO_2e$ or lower abatement cost) at currently projected energy prices.

Figure 3-2: Global Abatement Potential in Solvent Use: 2010, 2020, and 2030

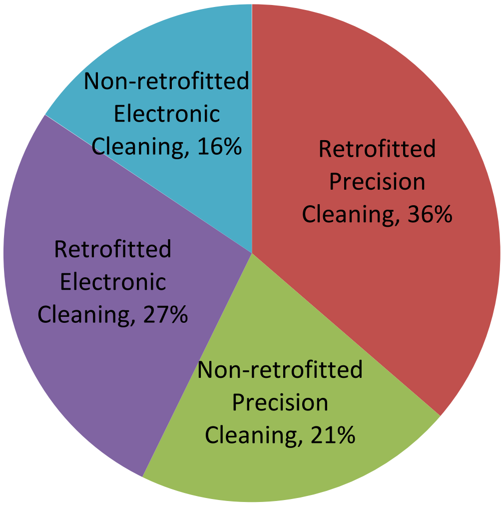


IV.3.2 Emissions from Solvents

Although solvents are primarily an emissive use, emissions from solvent applications are not equal to the amount of solvent consumed in a year because a portion of used solvent remains in the liquid phase and is not emitted as gas during use. However, as the solvent is continuously reused through a distilling and cleaning process or through recycling, it is assumed that eventually approximately 90% of the solvent consumed in a given year is emitted, while 10% of solvent is disposed of with the sludge that remains.

For the purpose of this analysis, the sector is characterized by precision cleaning applications and electronics cleaning applications. Precision cleaning requires a high level of cleanliness to ensure the satisfactory performance of the product being cleaned, and electronics cleaning is defined as a process that removes contaminants, primarily solder flux residues, from electronics or circuit boards. To develop the cost analysis, the model vapor degreaser is assumed to be 10 square feet in size, uses HFC-4310mee as a solvent, and emits 250 to 500 pounds of solvent annually, depending on whether the equipment has been retrofitted. Figure 3-3 presents the global distribution of HFC and PFC emissions from solvent use in 2020 by degreaser type.

Figure 3-3: Global HFC Emissions in 2020 by Degreaser Type (% of GWP-Weighted Emissions)



IV.3.2.1 Activity Data or Important Sectoral or Regional Trends

Solvent consumption, which is estimated using USEPA's Vintaging Model for the United States, is used to represent activity data. Solvent consumption is scaled according to country gross domestic product. Solvent emissions are directly correlated with solvent consumption; it is assumed that almost all (90%) of the solvent consumed in a given year is emitted. There are no regional differences in assumed emissions rates.

In developed countries, retrofits are assumed to have already been fully adopted, and in developing countries all equipment is assumed to remain nonretrofitted. In addition, although NIK replacement alternatives and HFE solvent applications currently exist worldwide, the baseline emissions considered here only covers that portion of the market still using HFCs and PFCs. Hence, for the purposes of transitioning away from the high GWP solvents in this analysis, there is no technology adoption of the NIK and HFE solvents in the baseline.

IV.3.2.2 Emission Estimates and Related Assumptions

Global emissions of HFCs from the solvents sector were 5 $MtCO_2e$ in 2010, growing to 10 $MtCO_2e$ in 2030. Table 3-1 presents the projected emissions for solvents use by country and regions between 2010 and 2030. All emissions are the result of HFC-4310mee consumption.[1] Emissions are projected to grow significantly as developing country economies grow and demand for such solvents grows. Emissions were estimated based on assumptions about initial market size of the sector, the specific transitions away from CFCs and other ODSs in terms of timing and alternative solvent used, charge sizes, and leak rates, using the Vintaging Model.

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[1] PFC solvent use in precision cleaning end-uses is assumed to discontinue such that no emissions of PFCs are projected beyond 2010 from this sector.

Table 3-1: Projected Baseline Emissions from Solvent Use: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	0.7	1.0	1.4	2.0	2.7	6.9%
United States	1.3	1.5	1.6	1.8	2.0	2.0%
Japan	0.9	1.0	1.0	1.1	1.2	1.2%
Russia	0.4	0.4	0.5	0.7	0.8	4.2%
South Korea	0.2	0.2	0.2	0.3	0.3	3.5%
Rest of Regions						
Africa	0.1	0.1	0.1	0.1	0.2	3.9%
Central & South America	0.2	0.2	0.2	0.3	0.3	3.3%
Middle East	0.0	0.0	0.0	0.1	0.1	3.8%
Europe	1.1	1.1	1.2	1.3	1.4	1.2%
Eurasia	0.0	0.0	0.0	0.0	0.0	4.2%
Asia	0.2	0.3	0.3	0.4	0.5	4.2%
North America	0.2	0.2	0.2	0.3	0.3	2.5%
World Total	**5.2**	**6.0**	**7.0**	**8.2**	**9.7**	**3.1%**

[a] CAGR = Compound Annual Growth Rate

Source: USEPA, 2012a

IV.3.3 Abatement Measures and Engineering Cost Analysis

A total of four abatement options were identified and analyzed for the solvent sector: (1) replacement of HFCs with HFEs, (2) retrofitting of equipment, (3) transition to NIK aqueous, and (4) transition to NIK semi-aqueous. Table 3-2 provides a technology overview of each abatement option.

Low-GWP alternatives for use in solvent applications are still emerging onto the market—perfluorobutyl iodide and Solstice 1233zd(E) are two such alternatives. The introduction of these substances involves regulatory approvals (such as the Significant New Alternatives Policy (SNAP) program evaluation process in the United States) followed by entry into the market and acceptance by users. These alternatives are discussed qualitatively in this chapter under "12.3.5 Low-GWP Alternatives."

Table 3-2: Solvent Use Abatement Options

Abatement Option	Reduction Efficiency	Applicability
HFC to HFE	76.4%	All facilities
Retrofit	50%	Nonretrofitted facilities
NIK aqueous	100%	Electronics cleaning
NIK semi-aqueous	100%	Electronics cleaning

IV.3.3.1 HFC to HFE

This option, which is applicable to all facilities in the baseline, examines the replacement of HFC-4310mee with lower GWP HFE solvents. Although other low-GWP chemicals may be feasible, HFE-7100 and HFE-7200 are used as proxies for this abatement option because they display material compatibility properties similar to HFCs, a prime factor that has led to their success in the market. To model emission reductions, this option assumes that the degreaser transitions to the use of 75% HFE-7100 and 25% HFE-7200.[2] For the purpose of this analysis, the 100-year GWP of alternative solvents is calculated as the weighted average of 75% HFE-7100, with a GWP of 390, and 25% HFE-7200, with a GWP of 55, for a GWP of 306.25. The GWP of the solvent being replaced, HFC-4310mee, is 1,300;[3] thus, this option has a reduction efficiency of 76.4%.

Costs associated with the conversion to HFE solvents are assumed to be negligible because of similarities in key chemical properties of HFE solvents and HFC-4310mee, as well as similar pricing structures.

IV.3.3.2 Retrofit

This abatement option is applicable to nonretrofitted facilities using solvents for the purpose of precision cleaning and electronics cleaning. Retrofits, including engineering control changes (e.g., increased freeboard height, installation of freeboard chillers, and use of automatic hoists), improved containment, and implementation of other abatement technologies can reduce emissions of HFCs used in solvent cleaning. Retrofitting a vapor degreaser, combined with proper operation and maintenance, can reduce solvent emissions from 46% to as much as 70%, depending on the specific retrofit methods chosen (Durkee, 1997). For example, installing a freeboard refrigeration device, sometimes referred to as a chiller (i.e., a set of secondary coils mounted in the freeboard), and maintaining a freeboard ratio of 1.0 to minimize diffusional solvent losses, can reduce emissions by 46%, while installing heating coils to produce superheated vapor along with installing a chiller can reduce emissions by 70%. For the purpose of this analysis, the reduction efficiency of the retrofit option is assumed to equal 50%.

In the United States, many enterprises have bought new equipment or retrofitted aging equipment into compliance with the National Emissions Standard for Hazardous Air Pollutants (NESHAP), which limits emissions from degreasers using traditional chlorinated solvents such as trichloroethylene. Fluorinated solvents such as HFCs are not covered by this regulation; nonetheless, a number of companies using HFCs and other nonchlorinated solvents have adopted NESHAP-compliant solvent cleaning machines because of the associated economic, occupational, and environmental benefits (i.e., reduced emissions) (Durkee, 1997). Likewise, many European countries have imposed stringent environmental and safety regulations that require the lowest level of emissions attainable by solvent degreasing equipment. Retrofit techniques were either already implemented or simply not required if the user had purchased new emission-tight vapor degreasers. Consequently, this analysis assumes that end

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[2] In actuality, a facility would choose one of the two HFEs for adoption; however, for modeling purposes this assumption was used to reflect the market presence of the two HFEs.

[3] Although the GWP value for HFC-4310mee was taken from the *IPCC Second Assessment Report* (1996), the report did not provide GWP values for either HFE. Consequently, this analysis uses the GWP values listed in the *IPCC Third Assessment Report* (2001) for both HFEs.

users in the United States and developed countries have already adopted these controls and that any emissions from these facilities cannot be further abated by this option. In contrast, solvent users in non-Annex I (i.e., developing) countries are assumed to not have retrofitted their equipment but may consider the equipment retrofit option, because updating their equipment may be preferred over investing in entirely new units.

Costs associated with adopting improved equipment and cleaning processes using existing solvents (retrofit) are incurred during the retrofit process and are estimated at $24,500 per degreaser. Annual savings of $4,500 are also realized through the avoided consumption of HFC that results from a reduction in emissions.

IV.3.3.3 Not-in-Kind Aqueous

This abatement option is applicable only to facilities that use solvents for the purposes of electronics cleaning. This option replaces HFC-containing systems used for electronic cleaning end uses with an aqueous cleaning process. In the aqueous process, a water-based cleaning solution is used as the primary solvent and is usually combined with a detergent to remove contaminants. Because all HFCs are replaced with a solvent that does not have a GWP, the reduction efficiency of this option is 100%.

Costs associated with adopting an aqueous NIK replacement alternative are assumed to be $50,000 for the initial investment and $7,400 annually due to energy and water consumption costs. However, annual savings are also assumed to result from not using an HFC-based cleaner; savings are estimated to range from $6,700 to $11,200 depending on whether the solvent-based cleaning system had been retrofitted, which will significantly offset annual costs.

IV.3.3.4 Not-in-Kind Semi-aqueous

This abatement option is applicable only to facilities that use solvents for the purposes of electronics cleaning. This option replaces HFC-containing systems used for electronic cleaning end uses with a semi-aqueous cleaning process. In the semi-aqueous process, the cleaning solution is an organic solvent that is blended with a surfactant, making it water soluble. An example of a solvent/surfactant blend is a terpene/water combination blended with glycol ethers. Because all HFCs are replaced with solvents that have no GWP, the reduction efficiency is 100%.

Costs associated with adopting a semi-aqueous NIK replacement alternative are assumed to be $55,000 for the initial investment and $9,100 annually due to energy and water consumption costs.[4] Annual savings are also assumed to result from not using an HFC-based cleaner; savings are estimated to range from $6,700 to $11,200 depending on whether the solvent-based cleaning system had been retrofitted.

IV.3.3.5 Low-GWP Alternatives

Two low-GWP alternatives, perfluorobutyl iodide (PFBI) and Solstice 1233zd(E), are also emerging options. Both substances are new alternatives that may potentially abate HFC and HFE emissions in

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[4] Although these costs are higher than the NIK aqueous abatement option, it is assumed that the semi-aqueous option will nonetheless be adopted in some facilities, for example where the NIK aqueous option might not be effective for the particular cleaning required.

solvent cleaning; however, it is too soon to determine reasonable market penetration and costs associated with the transition to such options.

Solstice 1233zd(E) is a hydrochlorofluoro-olefin and is also referred to as trans-1-chloro-3,3,3-trifluoroprop-1-ene. Solstice 1233zd(E) is part of a new class of solvents specifically designed with a low atmospheric lifetime, ODP, and GWP, making it a candidate to replace high GWP HFCs and low or moderate GWP HFE solvents, as well as saturated HCFCs in solvent cleaning applications (UNEP, 2012). It has a GWP of 4.7 to 7 (USEPA, 2012b) and is nonflammable, making it an attractive option for some markets. The United States is completing its evaluation of whether it can be considered acceptable for use in electronics, precision, and metals cleaning.

PFBI also has a low GWP of 5. In 2012, PFBI was listed by the US Significant New Alternatives Policy (SNAP) program as acceptable for use in electronics, metal, and precision cleaning (USEPA, 2012c). This substance may be feasible for the cleaning oxygen systems in the aerospace industry as a potential replacement for HCFC-225ca/cb because of its good cleaning performance (Mitchell and Lowrey, 2012); however, it is unclear the extent to which this solvent will be used in place of HCFCs as well as HFC and HFE solvents.

Given the low GWP of these and similar options under development, we could expect emission reductions to be similar to the NIK aqueous and semi-aqueous options under the same market penetration assumptions. However, because these chemicals can also compete with HFEs with mid-range GWPs and could avoid the energy and water consumption barriers seen with the NIK options, market penetration may be further or faster than the options analyzed here.

IV.3.3.6 Engineering Cost Data Summary

Table 3-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price. For more detailed costs see Appendix E.

Table 3-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility Type	Project Lifetime (years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
HFC to HFE	Retrofitted	15	—	—	—	113
	Nonretrofitted					136
Retrofit	Nonretrofitted	15	$24,500	$4,500	—	147
NIK aqueous	Electronic/Retrofitted	15	$50,000	$6,700	$7,400	147
	Electronic/Nonretrofitted			$11,200		295
NIK semi-aqueous	Electronic/Retrofitted	15	$55,000	$6,700	$9,100	147
	Electronic/Nonretrofitted			$11,200		295

IV.3.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the international assessment of abatement measures for solvents.

IV.3.4.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

IV.3.4.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions from model facilities in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time as systems are upgraded and the options are applied in the future. Table 3-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

Table 3-4: Technical Effectiveness Summary

Abatement Option	Technical Applicability	Market Penetration Rate (2030)	Reduction Efficiency	Technical Effectiveness
Precision—retrofitted	60%	100%	76%	46%
HFC to HFE				
Precision—nonretrofitted				
HFC to HFE	60%	80%	76%	37%
Retrofit	100%	20%	50%	10%
Electronics—retrofitted				
HFC to HFE	100%	80%	76%	61%
Aqueous	100%	10%	100%	10%
Semi-aqueous	100%	10%	100%	10%
Electronics—nonretrofitted				
HFC to HFE	100%	40%	76%	31%
Retrofit	100%	20%	50%	10%
Aqueous	100%	6%	100%	6%
Semi-aqueous	100%	6%	100%	6%

IV.3.4.3 Estimating Abatement Project Costs and Benefits

Table 3-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's monetary benefits equal to its costs. The previous section describes the assumptions used to estimate costs. The HFC to HFE option is available at no cost and represents 4.3 $MtCO_2e$ of reductions in 2030.

The break-even prices presented in Table 3-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors.

Table 3-5: Example Break-Even Prices for Abatement Measures in Solvent Use

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Precision—retrofitted					
HFC to HFE	113	—	—	—	—
Precision—nonretrofitted					
HFC to HFE	136	—	—	—	—
Retrofit	147	36.4	−30.5	7.4	−1.5
Electronics—retrofitted					
HFC to HFE	113	—	—	—	—
Aqueous	147	74.3	4.7	15.1	64.0
Semi-aqueous	147	81.8	16.3	16.6	81.4
Electronics—nonretrofitted					
HFC to HFE	136	—	—	—	—
Retrofit	147	36.4	−30.5	7.4	−1.5
Aqueous	295	37.2	−12.9	7.5	16.7
Semi-aqueous	295	40.9	−7.1	8.3	25.5

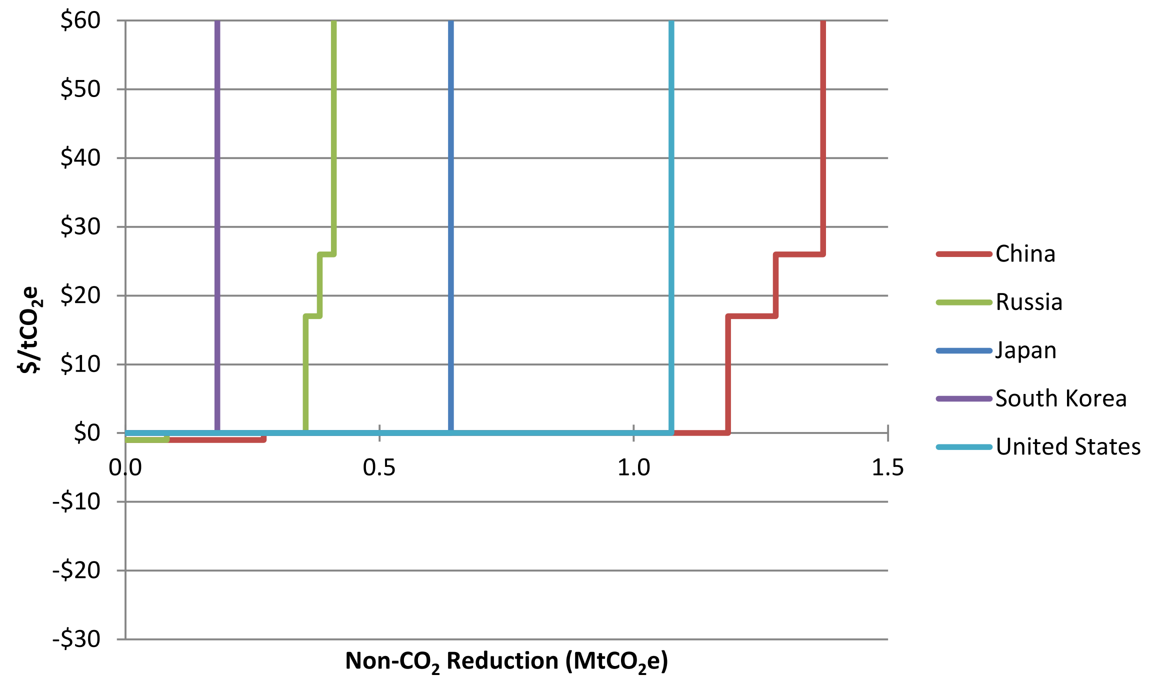
IV.3.4.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 3.0 and 5.7 $MtCO_2e$, respectively. There are 4.8 $MtCO_2e$ of reductions in 2030 resulting from implementing currently available technologies that are cost-effective at projected energy prices. The results of the MAC analysis are presented in Table 3-6 and Figure 3-4 by major country and regional grouping at select break-even prices in 2030.

Table 3-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break-Even Price ($\$/tCO_2e$)										
Country/Region	−10	−5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	1.2	1.2	1.2	1.2	1.3	1.4	1.4	1.4	1.4
Japan	—	—	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8
Russia	—	—	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
South Korea	—	—	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
United States	—	—	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.3	1.3
Rest of Region											
Africa	—	—	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Central and South America	—	—	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Middle East	—	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Europe	—	—	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.9	0.9
Eurasia	—	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Asia	—	—	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
North America	—	—	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
World Total	**—**	**—**	**4.8**	**4.8**	**4.8**	**4.8**	**5.0**	**5.1**	**5.1**	**5.7**	**5.7**

Figure 3-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



IV.3.5 Uncertainties and Limitations

This analysis assumes that all developed countries have already adopted retrofitted equipment while all developing nations are still using nonretrofitted equipment. This is a very simplistic assumption that may not adequately reflect regional differences in the adoption of retrofitted equipment. Additionally, the reductions associated with adopting retrofitted equipment are based on older sources that may no longer be applicable to the current market. Further research in this area is needed to refine both baseline estimates and the reduction potential associated with retrofits.

Another area of uncertainty in this analysis is related to how costs for the mitigation technologies may vary internationally. The analysis is currently limited due to the lack of region-specific cost information.

Also, it is assumed that the aqueous and semi-aqueous abatement options result in increased energy consumption (3M, 2008); however, the increase in CO_2 emissions associated with this energy use is not quantified as part of this analysis. To accurately capture net emission reductions of these abatement options, emissions associated with the increased energy use should also be calculated.

Finally, low-GWP alternatives for use in solvent applications are still emerging onto the market and could potentially replace HFCs and HFEs, further reducing projected emissions once adopted. This analysis does not project further abatement that can occur because of these alternatives as information on their potential uptake by the market and associated transition costs is unknown at this time.

References

3M. 2008. "Advantages of Solvent vs. Aqueous Cleaning." Electronic Market Materials Division. Available at: http://solutions.3m.com/wps/portal/3M/en_US/Novec/Home/Product_Information/Engineered_Fluids/.

3M Performance Materials. October 27, 2003. Written correspondence between industry technical expert John G. Owens, P.E., of 3M Performance Materials and Mollie Averyt and Marian Martin Van Pelt of ICF Consulting.

Brulin & Company, Inc. October 2008. Personal communication between Mike Beeks of Brulin & Company, Inc. and Emily Herzog and Mollie Averyt of ICF International.

Crest Ultrasonics. September/October 2008. Personal communication between Eric Larson of Crest Ultrasonics and Emily Herzog of ICF International.

Durkee, J.B. 1997. "Chlorinated Solvents NESHAP—Results to Date, Recommendations and Conclusions." Presented at the International Conference on Ozone Layer Protection Technologies in Baltimore, MD, November 12–13, 1997.

ICF Consulting. October 7, 2003. Personal communication between solvent industry experts and William Kenyon of ICF Consulting.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (ed.). Cambridge, United Kingdom: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment of the Intergovernmental Panel on Climate Change. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). Cambridge, United Kingdom and New York: Cambridge University Press, 881 pp.

Mitchell, M. and N. Lowrey. *The Search for Nonflammable Solvent Alternatives for Cleaning Aerosopace Oxygen Systems*. Presented at the 2012 International Workshop on Environment and Alternative Energy. Greenbelt, MD. December 4-7, 2012.

United Nations Environment Programme (UNEP). 2012. *Report of the Technology and Economic Assessment Panel: Decision XXIII/9 Task Force Report Additional Information on Alternatives to Ozone Depleting Substances*. Available at: http://conf.montreal-protocol.org/meeting/mop/mop-24/presession/Background%20Documents/teap-task-force-XXIII-9-report-may2012.pdf.

U.S. Environmental Protection Agency (USEPA). (2012a). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). 2012b. *Protection of Stratospheric Ozone: Determination 27 for Significant New Alternatives Policy (SNAP) Program*. 77 FR 47768-47779. Available at: http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/pdf/2012-19688.pdf.

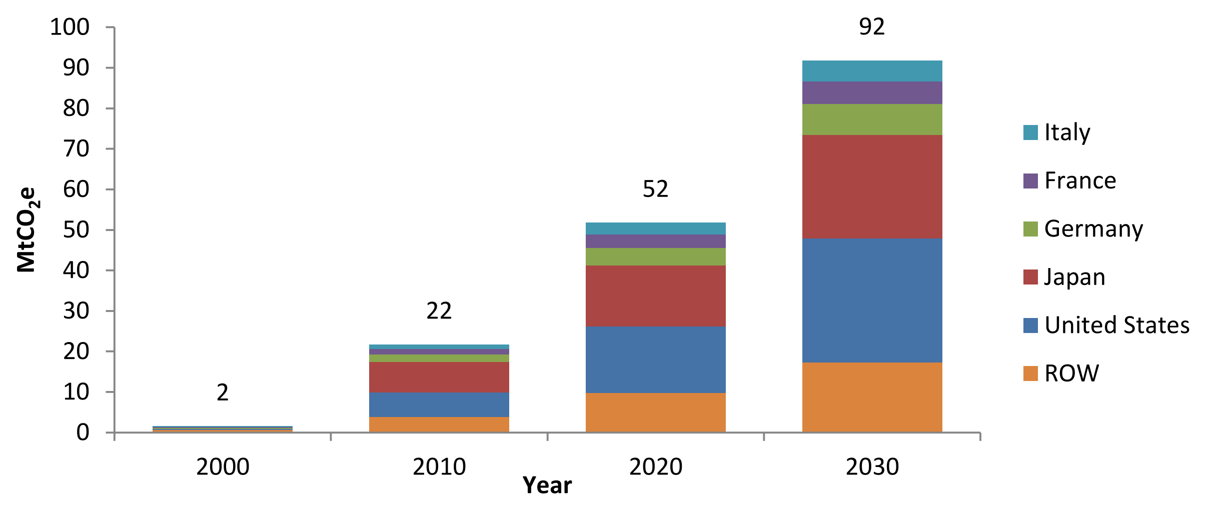
U.S. Environmental Protection Agency (USEPA). 2012c. *Substitutes in Non-aerosol Solvent Cleaning Under SNAP as of August 10, 2012*. Available at: http://www.epa.gov/ozone/snap/solvents/solvents.pdf.

IV.4. HFC Emissions from Foams Manufacturing

IV.4.1 Sector Summary

Foam is used as insulation in a range of equipment and products, including refrigerated appliances, reefers and other refrigerated transport systems, in buildings (e.g., walls, roofs, floors) and pipes, and to produce other products, such as steering wheels, furniture, and shoes, for example. A wide variety of foam types are used for these applications, which have historically been produced with blowing agents that are ozone-depleting substances (i.e., chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons [HCFCs]), but since the ODS phaseout under the Montreal Protocol, HFCs have commonly been adopted in their place—primarily HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc. Greenhouse gas emissions from the foams sector (excluding CFCs and HCFCs) were estimated at roughly 22 million metric tons of carbon dioxide (CO_2) equivalent ($MtCO_2e$) in 2010. By 2020, emissions from this sector are expected to reach over 52 $MtCO_2e$, as shown in Figure 4-1.

Figure 4-1: HFC Emissions from Foams Manufacturing: 2000–2030 ($MtCO_2e$)

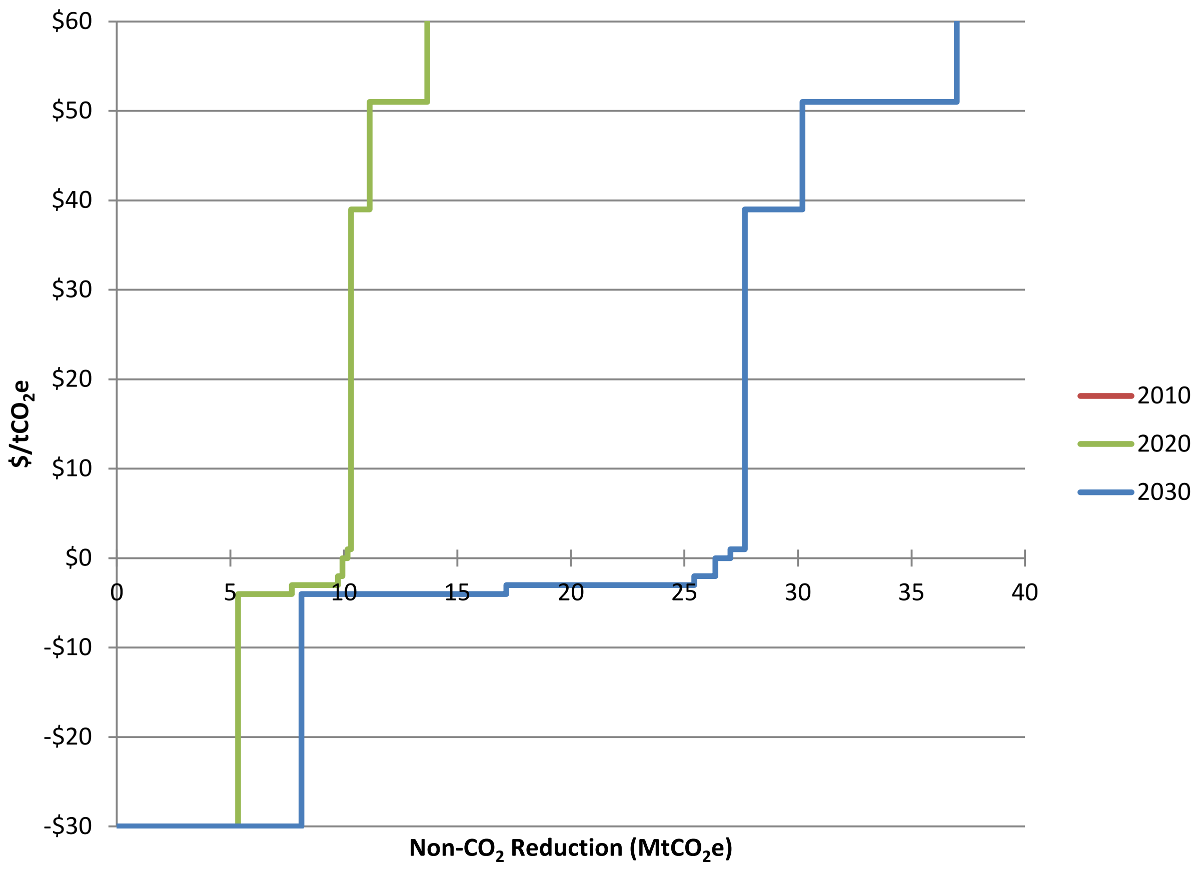


Source: USEPA, 2012a.

This analysis reviews options to reduce emissions from the foams sector by using low-global warming potential (GWP) foam-blowing agents in lieu of HFCs in new equipment/products and by recovering and destroying foam-blowing agents from household refrigerators at the end of the equipment's life.

Global abatement potential from the options reviewed equates to approximately 40.3% of total annual foam sector emissions and 21.9% of total emissions from ODS substitutes in 2030. While many options have been analyzed that can completely replace the HFC blowing agent in foams, abatement in the foams sector is limited by the lifetime of the installed base of foam products; all abatement opportunities analyzed replace the blowing agent in newly manufactured foams only, or destroy the blowing agent only at the foam natural end of life. Marginal abatement cost (MAC) curve results are presented in Figure 4-2. Maximum abatement potential in the foams sector is 37.0 $MtCO_2e$ in 2030. There are 27 $MtCO_2e$ of cost-effective emissions reductions in 2030, representing 29.4% of the foams baseline, based on the assumptions presented in this analysis. No reductions are available in 2010 as a result of the assumption that options did not start to penetrate the market until 2011.

Figure 4-2: Global Abatement Potential in Foams Manufacturing: 2010, 2020, and 2030



IV.4.2 Emissions from Foams

Although there are two main types of foams—open cell and closed cell—HFCs are primarily used in closed-cell foam applications for their physical and performance properties.[1] HFC blowing agents are emitted during product/equipment manufacture, use, disposal, and even following disposal (e.g., in landfills) if the foam substance is not specially treated. For the purpose of evaluating the cost of reducing HFC emissions from this sector, this analysis considers emissions from the following closed-cell foam applications: polyurethane (PU) appliance foam, PU commercial refrigeration foam, extruded polystyrene (XPS) boardstock foam, PU continuous and discontinuous panel foam, PU one-component foam, and PU spray foam. The relative GWP-weighted emission shares of these applications in 2020 are shown in Figure 4-3.

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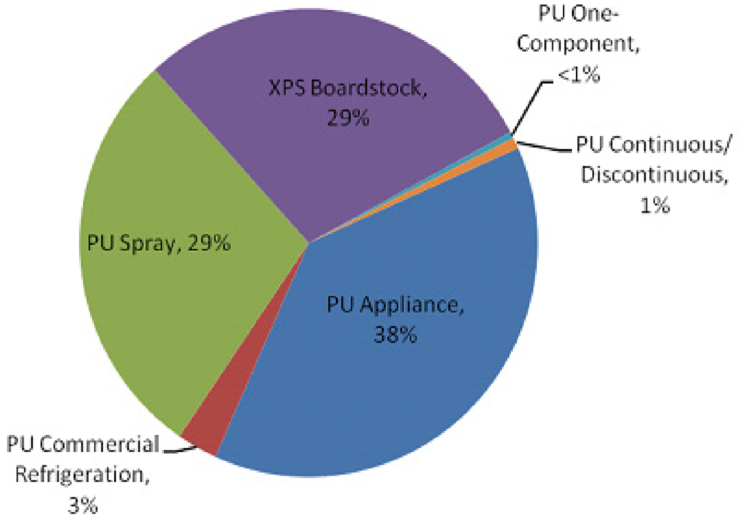
[1] Open cell foams experience significant blowing agent leakage due to the cell structure.

Figure 4-3: Global HFC Emissions in 2020 by Application Type (% of GWP-Weighted Emissions)



For the purpose of this analysis, the sector considers eight facilities and/or applications, as defined below.

- PU appliance foam manufacturing facility using HFC blowing agent: characterized as a typical manufacturing facility that produces 550,000 refrigerators per year and consumes nearly 537,000 kg of HFC-245fa blowing agent annually.
- PU commercial refrigeration foam manufacturing facility using HFC blowing agent: characterized as a typical manufacturing facility that produces 50,000 commercial units per year and consumes 70,000 kg of HFC-245fa blowing agent annually.
- PU spray foam contractor using HFC-245fa/CO_2 blowing agent: characterized as a typical PU spray foam contractor that uses nearly 58,000 kg of HFC-245fa/CO_2 PU spray foam annually.
- One-component foam manufacturing facility using HFC-134a or HFC-152a blowing agent: characterized as a typical facility that produces one-component foam and uses over 130,000 kg per year of HFC blowing agent.
- XPS boardstock production facility using HFC-134a/CO_2 blowing agent: characterized as a typical facility that creates approximately 1,000,000 board feet of XPS boardstock per year across 10 lines using nearly 7,100 kg of HFC-134a and CO_2 blowing agent.
- PU continuous and discontinuous foams manufacturing facility using HFC-134a blowing agent: characterized as a typical manufacturing facility that uses 453,000 kg of HFC-134a per year.
- Appliance demanufacturing facility using manual blowing agent recovery: characterized as a typical demanufacturing facility that manually processes 125,000 disposed domestic refrigerators per year.
- Appliance demanufacturing facility using fully automated blowing agent recovery: characterized as a typical demanufacturing facility that processes 200,000 domestic refrigerators per year using fully automated equipment.

For modeling purposes, data typical for facilities in the United States are used. Certain cost assumptions, such as capital costs, are adjusted for other regions.[2] Otherwise, it is assumed that the costs and reductions achieved in the modeled facilities could be scaled and would be representative of the costs and reductions in other regions.

IV.4.2.1 Activity Data, Important Sectoral or Regional Trends and Related Assumptions

Foam consumption for the United States is estimated using the U.S. Environmental Protection Agency's (USEPA's) Vintaging Model. This consumption and associated emissions are assumed to scale with country gross domestic product (GDP), with several regional adjustments made to account for differences in HFC foam consumption based on data provided in FTOC (2010). Specifically, in the European Union, HFC consumption for XPS boardstock and commercial refrigeration is assumed to be lower than in the United States, because of a faster transition to low-GWP alternatives, while no HFC consumption is assumed in the PU appliance subsector (because the transition away from HFCs is already complete). Similarly, in developing countries, no HFC consumption is assumed in PU appliance, commercial refrigeration, XPS boardstock, PU spray, and PU continuous and discontinuous foams, because these subsectors are transitioning directly from ODS to non-HFC low-GWP alternatives. Additionally, a reduced proportion of HFC consumption in PU one-component foam is assumed in developing countries relative to the U.S. subsector (with consumption assumed only for HFC-134a, not HFC-152a).

IV.4.2.2 Emission Estimates and Related Assumptions

Global HFC emissions from foams were estimated at 22 $MtCO_2e$ in 2010, projected to grow to 52 $MtCO_2e$ by 2020 and 92 $MtCO_2e$ by 2030. Growth in emissions is driven by GDP. Globally, HFC emissions from foam production and use have been growing because of the phaseout of ODS under the Montreal Protocol. Because of the costs associated with HFC-based foams, many countries have transitioned/are transitioning from ODS to hydrocarbons or other non-HFC alternatives. Because of developing countries' minimal use of HFCs, the growth in global emissions for the past decade has been driven by emissions from developed countries. Consumption is modeled based on USEPA's Vintaging Model, with emissions estimated based on assumed blowing agent loss rates at manufacture, during lifetime, and at disposal—which vary by foam application and blowing agent type. Emissions for major countries and regions are presented in Table 4-1.

IV.4.3 Abatement Measures and Engineering Cost Analysis

This analysis considers the costs of reducing foam emissions by (1) replacing HFCs with low-GWP blowing agents in various types of foam manufacturing operations and (2) properly recovering and disposing of foam contained in the equipment at the end of its life. Specifically, eight abatement options were identified and analyzed for reducing emissions at product/equipment production by using hydrocarbon (HC) or CO_2 blowing agents in place of HFCs, and two options were identified for reducing

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[2] In developing countries, it is assumed that capital costs are 10% higher than those in the United States.

Table 4-1: Projected Baseline Emissions from Foams Manufacturing: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
United States	6.1	8.7	16.4	23.0	30.5	8.4%
Japan	7.6	10.0	15.0	19.7	25.5	6.3%
Germany	1.7	2.4	4.4	5.9	7.7	7.7%
France	1.3	1.7	3.2	4.3	5.6	7.7%
Italy	1.2	1.6	2.9	3.9	5.1	7.7%
Rest of Regions						
Africa	—	—	—	—	—	0.0%
Central & South America	—	—	—	—	—	0.0%
Middle East	—	—	—	—	—	0.0%
Europe	3.0	4.1	7.7	10.2	13.4	7.7%
Eurasia	0.1	0.2	0.3	0.4	0.5	6.5%
Asia	0.2	0.3	0.5	0.8	1.1	9.4%
North America	0.5	0.7	1.3	1.8	2.4	8.4%
World Total	**21.7**	**29.6**	**51.8**	**70.0**	**91.8**	**7.5%**

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA), 2012a.

emissions at the end of the equipment's life by using various methods of foam recovery at the time of appliance disposal. These options are described in the subsections below and summarized in Table 4-2. Additional details of the calculations are provided in Appendix F to this chapter.

Additional options considered, but not yet included in the cost analysis, are examined in Sections 4.3.11 through 4.3.13, after the 10 options listed in Table 4-2 are discussed. These and other options not mentioned are also potentially available but have not been included in this analysis due to data availability and time.

Table 4-2: Foams Manufacturing Abatement Options

Abatement Option	Reduction Efficiency	Applicability
Appliance: HFCs to HCs	100%	New PU appliances
Commercial refrigeration: HFCs to HCs	100%	New PU commercial refrigeration units
Spray: HFC245fa/CO_2 to HC	100%	New spray foam applications
Spray: HFC245fa/CO_2 to CO_2	100%	New spray foam applications
XPS: HFC134a/CO_2 to LCD/alcohol	100%	New XPS boardstock foam applications
One component: HFC-134a to HCs	100%	New PU one-component foam applications
One component: HFC-152a to HCs	100%	New PU one-component foam applications
Continuous and discontinuous: HFC134a to HCs	100%	New PU continuous and discontinuous foam applications
Appliance EOL: Manual process	85%	Domestic refrigerators reaching end of life
Appliance EOL: Fully automated process	95%	Domestic refrigerators reaching end of life

IV.4.3.1 HCs in PU Appliances

This option replaces HFC-245fa used in PU appliance foam with HCs. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using HCs, including flammability, and lower insulation performance (USEPA, 2009), but these can be overcome through proper safety controls and engineering design. A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Approximately 50% of hydrocarbons used in appliances are based on cyclopentane and isopentane, due to their low operating costs and good foam properties (UNEP, 2010; TEAP, 2012). Cyclopentane has also been blended with isobutene to improve flow-ability and compressive strength, or with methylal, to improve performance (UNEP, 2010). Flammability, however, may cause a high incremental capital cost for facilities, which may be uneconomic for small or medium-sized enterprises; otherwise, HCs have low operating costs (TEAP, 2012). Using HCs instead of HFC-245fa in PU appliance foam eliminates HFC emissions at all stages of the product life cycle (i.e., at manufacturing, during appliance use, and at appliance disposal).

This option applies to HFC-245fa in newly manufactured PU appliance foam. This option is not applied in the European Union or in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at approximately $4.8 million per facility for safety modifications, installation/retrofit of high-pressure foam dispensers, installation of systems storage tanks, pumps, and premixing stations, as well as training, trials, testing, and certification (TEAP, 2012; UNEP, 2011a). Incremental annual costs associated with replacement formulations are estimated at approximately $1.6 million (UNEP, 2011a). These annual costs are more than offset by annual savings of nearly $4.4 million associated with lower blowing agent costs.

IV.4.3.2 HCs in Commercial Refrigeration

This option replaces HFC-245fa used in commercial refrigeration foam with HCs, namely cyclopentane and cyclopentane/isopentane blends. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using hydrocarbons, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design. A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Use of cyclopentane and cyclo/iso blends in commercial refrigeration has a particularly good balance between foam properties and density. Such HC blends are associated with low operating costs and are well-proven (UNEP, 2010; TEAP, 2012). Flammability, however, may cause a high incremental capital cost for facilities, which may be uneconomic for small or medium-sized enterprises; otherwise, hydrocarbons have low operating costs (TEAP, 2012).

This option applies to HFC-245fa in newly manufactured PU commercial refrigeration foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at about $1.26 million per facility associated with safety modifications, installation/retrofit of high-pressure foam dispensers, installation of hydrocarbon storage systems, pumps, and premixing stations, as well as, safety audits, trials, and training (TEAP, 2012; UNEP, 2011b). Incremental annual costs associated with replacement formulations are estimated at nearly $105,000 (UNEP, 2011b). These annual costs are more than offset by annual savings of about $602,000 associated with lower blowing agent costs.

IV.4.3.3 HC in Polyurethane Spray Foams

This option replaces HFC-245fa/CO_2 used in PU spray foam with HCs, specifically an 80/20 blend of cyclopentane and isopentane. HCs are inexpensive and have near-zero direct GWPs. However, it should be noted that technical issues exist with using hydrocarbons, including flammability, which may render this alternative unsafe in some spray applications (TEAP, 2012). Using HCs instead of HFC-245fa/CO_2 in PU spray foam would eliminate HFC emissions during application (first year) and over the product lifetime (USEPA, 2009).

This option applies to all HFC-245fa/CO_2 in newly manufactured PU spray foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at $15,700 per contractor for new formulations and equipment (e.g., spray nozzles), while annual operating costs are estimated at $45,200 for fire retardant, worker safety training, and cost increases from blowing agent density change. These annual costs are offset by annual savings of $50,400 associated with lower blowing agent costs.

IV.4.3.4 CO2 in Polyurethane Spray Foams

This option replaces HFC-245fa/CO_2 blends used in PU spray foam with CO_2 (water). In the process of using CO_2 (water) in foams, first isocyanate and the polyol or polyamine react to form a polymer, which forms a solid. Water is introduced and a chemical reaction between the water and polymeric isocyanate produces CO_2, which is used as a blowing agent. Using CO_2 (water) instead of HFC-245fa in PU spray foams eliminates HFC emissions during the production and application stages and over the product lifetime (USEPA, 2009). CO_2 is considered to have moderate foam properties (due to its high thermal conductivity and high density), and requires greater thickness that leads to a cost penalty compared to other options (TEAP, 2012). The use of CO_2 in this application is most predominant in Japan, with reported use also in North America and Spain (UNEP, 2010).

This option applies to all HFC-245fa/CO_2 in newly manufactured PU spray foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at $4,600 per contractor (for new formulations and minimal equipment modifications), while annual operating costs are estimated at $60,700 (for fire retardant and the cost increase from blowing agent density change). These annual costs are partly offset by annual savings of $10,700 associated with lower agent costs.

IV.4.3.5 LCD/Alcohol in XPS Boardstock

This option replaces the HFC-134a and CO_2-based blends used in extruded polystyrene (XPS) boardstock foam with liquid CO_2 (LCD)/alcohol. LCD is blended with other foam components under pressure prior to the initiation of the chemical reaction. When decompressed, the CO_2 expands, resulting in froth foam that further expands with the additional release of CO_2 from the water/isocyanate resin reaction that forms the PU foam matrix. Difficulties encountered in using LCD include the limited solubility of the chemical mixture, controlled decompression, and distribution of the unavoidable froth (USEPA, 2009). Foams blown with CO_2 may suffer from lower thermal performance, lower dimensional stability, and higher density versus fluorocarbon-blown foams (USEPA, 2009). To overcome these limitations, CO_2 can be blended with HCs or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001).

This option applies to all HFC-134a/CO_2 blends in newly manufactured XPS boardstock foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. This analysis assesses the costs for the foam producer to replace an HFC-134a/CO_2-based blend with LCD/alcohol in one of 10 production lines. One-time costs are estimated at

$5,856,000 per facility (for equipment, safety, and incineration considerations), while annual operating costs are estimated at $915,000 (for labor, energy, and lost capacity). These annual costs are offset by annual savings of $4,770,000 associated with lower costs for agent and polystyrene resin.

IV.4.3.6 HFC-134a to HCs in PU One-Component Foam

This option replaces HFC-134a used in PU one-component foam with HCs, specifically a 50/50 blend of propane and butane. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using HCs, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design (USEPA, 2009). A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Use of butane and propane in one component foams is well proven and is associated with low operating costs (TEAP, 2012). Using HCs instead of HFC-134a in PU one-component foams eliminates HFC emissions during manufacturing and over an assumed product lifetime of 1 year (USEPA, 2009).

This option applies to all HFC-134a in newly manufactured PU one-component foam in both developed and developing countries. One-time costs are estimated at $399,000[3] per facility (for capital costs and safety equipment), while annual operating costs are estimated at $342,000 (for fire retardant and worker safety training). These annual costs are offset by annual savings of $859,000 associated with lower agent costs.

IV.4.3.7 HFC-152a to HCs in PU One-Component Foam

Similar to the option above, this option replaces HFC-152a used in PU one-component foam with HCs, specifically a 50/50 blend of propane and butane.

This option applies to all HFC-152a in newly manufactured PU one-component foam. This option is not applied in developing countries, because no baseline HFC-152a consumption is assumed in this application. One-time costs are estimated at $399,000 per facility (for capital costs and safety equipment), while annual operating costs are estimated at $342,000 (for fire retardant and worker safety training). These annual costs are offset by annual savings of $409,000 associated with lower agent costs.

IV.4.3.8 HCs in PU Continuous and Discontinuous Foams

This option replaces HFC-134a used in PU continuous and discontinuous panel foam with HCs. HCs are inexpensive and have near-zero direct GWPs. Some technical issues exist with using HCs, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design (USEPA, 2009). A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Using HCs instead of HFC-134a in PU continuous and discontinuous panel foam eliminates HFC emissions during the manufacturing stage, during the foam's assumed 50-year lifetime, and at time of product disposal (USEPA, 2009).

This option is assumed to be applicable to all HFC-134a in newly manufactured PU continuous and discontinuous panel foam. This option is not applied in developing countries, because no HFC

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[3] In developing countries, it is assumed that capital costs are 10% higher than those in the United States.

consumption is assumed in this application in the baseline. One-time costs are estimated at $319,000 per facility (for capital costs and safety equipment), while annual operating costs are estimated at $2,490,000 (for fire retardant, worker safety training, and changes in foam density). These annual costs are offset by annual savings of $2,937,000 associated with lower agent costs.

IV.4.3.9 Manual Blowing Agent Recovery from Appliances at End of Life (EOL)

In most countries,[4] foams contained in appliances and other products typically end up in landfills, where the remaining blowing agent still contained in the insulation at the end of the product's life is released during shredding and compaction or slowly over time (CARB, 2011). This option involves manual labor to disassemble appliances and remove the foam in large pieces; the recovered foam is then sealed in plastic bags to prevent further off-gassing of the blowing agent and subsequently sent for incineration in a waste-to-energy plant. This practice is currently being used in the United States and Canada, where voluntary programs and/or demand-side management programs are in place to encourage the safe disposal of inefficient appliances (CARB, 2011).

This abatement option applies to existing domestic refrigerators reaching disposal. This option is not applied in the European Union or in developing countries, because no baseline HFC consumption is assumed in PU appliances (further, recovery of foam at appliance equipment EOL is assumed in the EU baseline). One-time costs are estimated at $1 million per facility (for automated saws), while net annual operating costs are estimated at $4,865,000 per facility for labor and handling costs (CARB, 2011).

IV.4.3.10 Fully Automated Blowing Agent Recovery from Appliances at EOL

Similar to the previous option, this option involves the recovery of foam at the end of the appliance's life, but instead using fully automated appliance dismantling machines that separate all components, including the foam-blowing agent. The blowing agent is then reconcentrated and sent to a destruction facility approved to destroy ODS, while the remaining foam fluff is typically sent to a landfill. Fully automated appliance recycling technologies can handle an estimated annual throughput of 150,000 to 250,000 units (CARB, 2011).

This abatement option applies to existing domestic refrigerators reaching disposal. This option is not applied in the European Union or in developing countries, because no baseline HFC consumption is assumed in this application. One-time costs are estimated at $5,000,000 per facility (for the fully automated unit), while net annual operating costs are estimated at $6,130,000 per facility for labor, handling, and electricity costs (CARB, 2011).

IV.4.3.11 Solstice Liquid Blowing Agent in PU Foams

Solstice Liquid Blowing Agent[5] produced by Honeywell (also referred to as Solstice LBA, Solstice 1233zd(E), or Trans-1-chloro-3,3,3-trifluoroprop-1-ene) is under development/in early commercialization

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[4] Foam recovery from disposed appliances is already mandatory in a number of countries, including Japan and the European Union.

[5] Other unsaturated HFCs and HCFCs with low GWPs are being developed by DuPont and Arkema, among others, for use in PU and other foam applications, which are likely to be commercialized in the coming years. Although these compounds are not yet commercialized, they may be expected to have similar GWPs and applications as the Solstice compounds described here.

to replace HFC-134a and HFC-245fa used in a range of PU foam applications, including appliance foam, commercial refrigeration foam, continuous and discontinuous panel foam, and spray foam (TEAP, 2012). The blowing agent has been approved in the United States, Japan, European Union (up to 10MT), India, and Asia Pacific, South America, Central America, Middle East, and Africa regions (Honeywell, 2012a). The first commercial manufacture is expected to occur in 2013 (TEAP, 2012). Recently, Whirlpool announced that by 2014, Solstice LBA will be used in all of the company's refrigerators produced in the United States (Whirlpool, 2012). Solstice LBA has a GWP of 4.7 to 7 (USEPA, 2012b). The foam blowing agent is also considered to be nonflammable (Honeywell, 2012a), which could limit capital costs to convert from an HFC to this product. Solstice LBA exhibits relatively high performance and is considered a drop-in alternative to HFCs, with no additional capital costs (TEAP, 2012). Any significant cost is expected to be the result of the incremental cost of the blowing agent, which is expected to range from \$11/kg to \$17/kg (TEAP, 2012; Williams, 2013), but which may be lower, especially once production volume increases. Recent evaluations showed up to a 4% improvement in energy efficiency compared to HFC-245fa in domestic refrigerators (TEAP, 2012; Honeywell, 2012a), and a 5% to 10% energy performance improvement compared to HFC-245fa in spray and panel foams (Honeywell, 2012a), making it an attractive and likely option for markets where thermal insulation properties of the foam are important, such as in domestic refrigerators. With its low GWP, Solstice 1233zd(E) could be used in lieu of HC abatement options analyzed above for PU foams applications and achieve similar emission reductions, but at different costs. Because it is nonflammable and of similar properties as the HFCs it would replace, it would avoid some of the barriers due to pressure and flammability that exist with the other options, such as in PU spray foam, and hence may penetrate those markets further or faster than the options currently analyzed. This option is not quantitatively assessed in this analysis but may be added as a future update.

IV.4.3.12 Solstice Gas Blowing Agent in XPS Foam and One-Component Foam

Solstice Gas Blowing Agent[6] (also referred to as Solstice GBA, Solstice 1234ze(E), and HFO-1234ze) can replace HFC-134a used in PU one-component foam and is under development/in early commercialization to replace HFC-134a in XPS foam beginning in 2013. The blowing agent has been commercial since 2008, with initial sales starting in the EU and Japan; approval for sales in the United States was awarded in 2011 (Honeywell, 2012a). The GWP of Solstice GBA is <6 and it is considered to be nonflammable up to temperatures of 28°C (82.4°F) (TEAP, 2012). In XPS foam, Solstice GBA has shown good insulation performance (i.e., energy efficiency) and compressive strength and dimensional stability similar to HFC-134a, and allows extrusion of thick foam (Honeywell, 2012a), making it an attractive and likely option for markets where such properties of the foam are important, such as in XPS foam. Solstice GBA can be used as a near drop-in replacement for HFC-134a, and can be handled, transported, and stored in the same manner (Honeywell, 2012b). Transition to Solstice GBA is anticipated to require negligible capital costs (TEAP, 2012; Williams, 2013). Any significant cost is expected to be the result of the incremental cost associated with the blowing agent, which is estimated to range from \$11/kg to \$17/kg (TEAP, 2012; Williams, 2013) but which may be lower, especially once production volume increases. With its low GWP, HFO-1234ze(E) could be used in lieu of LCD/alcohol in XPS foam and hydrocarbons in one-

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[6] Other unsaturated HFCs and HCFCs with low GWPs are being developed by DuPont and Arkema, among others, in XPS, one-component, and other foam, which are likely to be commercialized in the coming years. These compounds may be expected to have similar GWPs and applications as the Solstice compounds described here.

component foam and achieve similar emission reductions, but at different costs. Because it is nonflammable and of similar properties as the HFCs it would replace, it would avoid some of the barriers due to controlling decompression and flammability that exist with the other options, and hence may penetrate those markets further or faster than the options currently analyzed. This option is not quantitatively assessed in this analysis but may be added as a future update.

IV.4.3.13 Methyl Formate in PU and XPS Foams

Methyl formate may replace HFCs in commercial refrigeration, continuous and discontinuous panels, spray foam, transport refrigeration foam, and XPS foam. It is currently used in PU spray foams internationally, including Africa, Asia, Americas, Australia, China, and Europe (Ecomate, 2012). Methyl formate was approved as a "Generally Recognized as Safe" substance by the U.S. Food and Drug Administration (Ecomate, 2012) and has a negligible GWP (TEAP, 2012). It may be blended with polyols to produce non-flammable blends that reduce conversion costs (TEAP, 2012). In commercial refrigeration and panel foam, corrosion protection is recommended and may require moderate incremental capital costs (TEAP, 2012). This option is reportedly associated with a 10% increase in operating costs due to the need for higher densities to address foam instability (UNEP, 2010). Generally, use of this alternative does not require large capital changes to facilities (Ecomate, 2012). One producer of rigid foams for refrigerated transport applications in Brazil completed conversion to methyl formate within 3 years and has since reported an increase in the productivity of the lines and reduced operational costs compared to HFC-134a (Crestani, 2012). Relative to hydrocarbon systems, methyl formate is safer to handle, and has lower shipping, handling, and storage costs (Ecomate, 2012). The GWP of methyl formate is similar to that of the options examined in this report; hence, emission reductions would be similar. Due to a lack of readily available cost information on this alternative, this option is not quantitatively assessed in this analysis.

IV.4.4 Engineering Cost Data Summary

Table 4-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

Table 4-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility Type	Project Lifetime (Years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
Appliance: HFCs to HCs	PU appliance foam manufacturing facility	25	$4,831,000	$4,375,000	$1,610,000	509,951
Commercial refrigeration: HFCs to HCs	PU commercial refrigeration foam manufacturing facility	15	$1,260,000	$602,000	$105,000	66,500
Spray: HFC245fa/CO2 to HC	PU spray foam contractor	25	$15,700	$50,400	$45,200	54,654
Spray: HFC245fa/CO2 to CO2	PU spray foam contractor	25	$4,600	$10,700	$60,700	54,654
XPS: HFC134a/CO2 to LCD/alcohol	XPS boardstock production facility	25	$5,856,000	$4,770,000	$915,000	9,168
One-component: HFC-134a to HCs — Developed	One-component foam manufacturing facility	25	$399,000	$859,000	$342,000	169,603

(continued)

Table 4-3: Engineering Cost Data on a Facility Basis (continued)

Abatement Option	Facility Type	Project Lifetime (Years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
One-component: HFC-134a to HCs—Developing	One-component foam manufacturing facility	25	$438,900	$859,000	$342,000	169,603
One-component: HFC-152a to HCs	One-component foam manufacturing facility	25	$399,000	$409,000	$342,000	18,265
Continuous and discontinuous: HFC134a to HCs	PU continuous and discontinuous foams manufacturing facility	25	$319,000	$2,937,000	$2,490,000	588,900
Appliance EOL: Manual process	Appliance demanufacturing facility using manual blowing agent recovery	25	$1,000,000	—	$4,865,000	99,380
Appliance EOL: Fully automated process	Appliance demanufacturing facility using fully automated blowing agent recovery	25	$5,000,000	—	$6,130,000	177,716

IV.4.5 Marginal Abatement Cost Analysis

IV.4.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option and facility or operation. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline (that is, the HFC emissions from sectors that historically used ODSs) attributable to each representative facility/operation and the technical effectiveness for each technology in each facility.

IV.4.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by facility in addition to process-specific estimates of technical applicability and market penetration. Market penetration is a modeled value that takes into account the market's willingness to adopt the option, the rate of uptake of the alternative into new foams, and the lifetime of the existing foam base. Because foam lifetimes can be decades, replacing the stock of foams with non-HFC blowing agents will take many years. The market penetration rate is modeled to capture such time lapses. Technical effectiveness figures do not account for indirect greenhouse gas impacts associated with changes in electricity consumption (e.g., for foam blowing processes or for end-of-life appliance processing), which are accounted for in the cost analysis.[7] Table 4-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

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[7] Indirect greenhouse gas emissions are not accounted for in the technical effectiveness calculations so that the analysis can show purely ODS substitute (i.e., HFC) emission reductions achievable. It is recognized that indirect GHG emissions can be significant, and such differences, to the extent data is available on such, are accounted for in the cost analyses.

Table 4-4: Technical Effectiveness Summary

Facility/Abatement Option	Technical Applicability	Market Penetration Rate (2030)[a]	Reduction Efficiency	Technical Effectiveness (2030)[b]
Appliance: HFCs to HCs—U.S./Other developed	New PU appliances	100%	100%	37%
Commercial refrigeration: HFCs to HCs—Developed	New PU commercial refrigeration units	100%	100%	39%
Spray: HFC245fa/CO2 to HC—Developed	New spray foam applications	30%	100%	9%
Spray: HFC245fa/CO2 to CO2—Developed	New spray foam applications	70%	100%	22%
XPS: HFC134a/CO2 to LCD/Alcohol—U.S./Other developed	New XPS boardstock foam applications	75%	100%	66%
XPS: HFC134a/CO2 to LCD/Alcohol—EU	New XPS boardstock foam applications	75%	100%	55%
One-component: HFC-134a to HCs—Developed & developing	New PU one-component foam applications	100%	100%	94%
One-component: HFC-152a to HCs—Developed	New PU one-component foam applications	100%	100%	6%
Continuous and Discontinuous: HFC134a to HCs—Developed	New PU continuous and discontinuous foam applications	100%	100%	49%
Appliance EOL: Manual process—U.S./Other developed	Domestic refrigerators reaching end of life	50%	85%	29%
Appliance EOL: Fully automated process—U.S./Other developed	Domestic refrigerators reaching end of life	20%	95%	12%

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in the appendix F to this chapter.

[b] Technical effectiveness figures represent the percent of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts associated with increased electricity consumption (e.g., for foam blowing processes or for end-of-life appliance processing), which are accounted for in the cost analysis.

IV.4.5.3 Estimating Abatement Project Costs and Benefits

Table 4-5 provides examples of the break-even prices calculated for each abatement measure. Project costs and benefits are calculated for model facilities and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate costs for each technology for applicable facilities. Additional details on the analyses can be found in Appendix F to this chapter.

The break-even prices presented in Table 4-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section IV.4.5.4.

Table 4-5: Example Break-Even Prices for Abatement Measures in Foams Manufacturing

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Appliance: HFCs to HCs	509,951	1.7	−5.4	0.3	−3.9
Commercial refrigeration: HFCs to HCs	66,500	4.2	−7.5	0.8	−4.2
Spray: HFC245fa/CO2 to HC	54,654	0.1	−0.1	0.0	−0.1
Spray: HFC245fa/CO2 to CO2	54,654	0.0	0.9	0.0	0.9
XPS: HFC134a/CO2 to LCD/Alcohol	9,168	117.3	−420.5	17.0	−320.2
One-component: HFC-134a to HCs—Developed	169,603	0.4	−3.0	0.1	−2.7
One-component: HFC-134a to HCs—Developing	169,603	0.5	−3.0	0.1	−2.6
One-component: HFC-152a to HCs	18,265	4.0	−3.7	0.6	−0.2
Continuous and discontinuous: HFC134a to HCs	588,900	0.1	−0.8	0.0	−0.7
Appliance EOL: Manual process	99,380	1.8	49.0	0.3	50.5
Appliance EOL: Fully automated process	177,716	5.2	34.5	0.8	38.9

IV.4.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 13.7 and 37.0 $MtCO_2e$, respectively. There are 27.0 $MtCO_2e$ of reductions available in 2030 resulting from implementing currently available technologies that are economical at projected costs. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to manufacturers/users of foams, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 4-6, which shows abatement potential by major country and regional grouping at select break-even prices in 2030; Figure 4-4 illustrates the marginal abatement cost curves of the top five emitting countries.

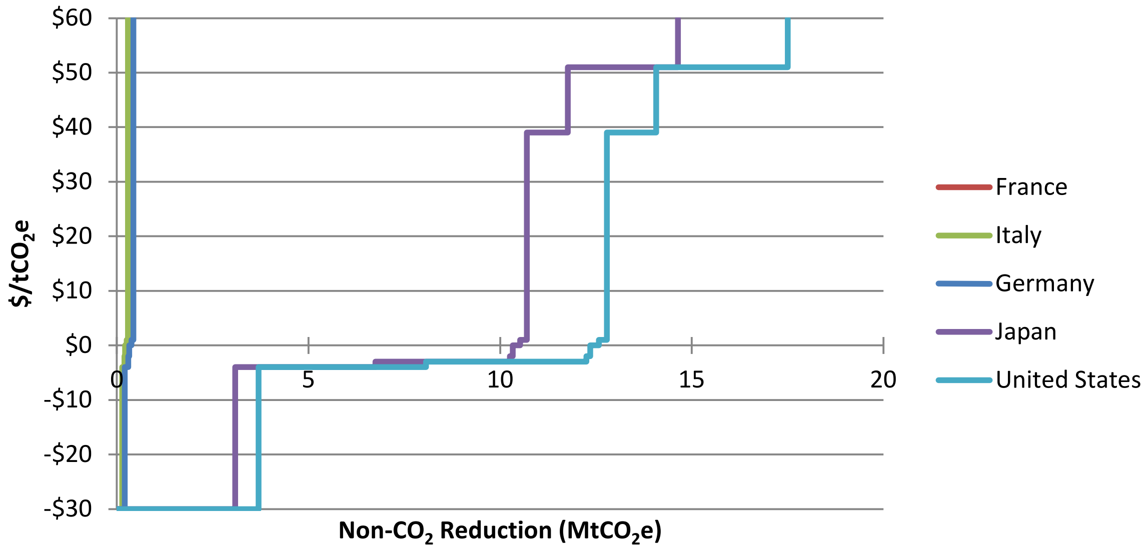
IV.4.6 Uncertainties and Limitations

Available data on costs for abatement technologies were not scaled to reflect potential differences in the costs outside of the United States. Additional research may be required to determine actual variability in costs across regions. Moreover, the development of alternative blowing agents is quickly evolving; thus, new options may enter the market, which should be considered quantitatively in future analyses (e.g., unsaturated fluorinated compounds and methyl formate).

Table 4-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break-Even Price ($\$/tCO_{2e}$)										
Country/Region	**−10**	**−5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100 +**
Top 5 Emitting Countries											
France	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Germany	0.2	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Italy	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Japan	3.1	3.1	10.5	10.7	10.7	10.7	10.7	10.7	11.8	14.6	14.6
United States	3.7	3.7	12.6	12.8	12.8	12.8	12.8	12.8	14.1	17.5	17.5
Rest of Region											
Africa	—	—	—	—	—	—	—	—	—	—	—
Central and South America	—	—	—	—	—	—	—	—	—	—	—
Middle East	—	—	—	—	—	—	—	—	—	—	—
Europe	0.4	0.4	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3
Eurasia	-	-	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Asia	0.1	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
North America	0.3	0.3	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.4	1.4
World Total	**8.1**	**8.1**	**27.0**	**27.7**	**27.7**	**27.7**	**27.7**	**27.7**	**30.2**	**37.0**	**37.0**

Figure 4-4: Marginal Abatement Cost Curves for Top Five Foam Emitters in 2030



References

Alliance for Responsible Atmospheric Policy. 2001. *Review of EPA Draft Chapter 9 by Members of the Alliance for Responsible Atmospheric Policy.* Alliance. May 16, 2001.

Caleb. 2000. *In response to Proposed Rulemaking 65 Fed. Reg. 42653, July 11th 2000.* Caleb Management Services Limited, UK (p. 3).

CARB. September 2011. *Lifecycle Analysis of High Global Warming Potential Greenhouse Gas Destruction.* Prepared by ICF International.

Crestani, Felipe (Folle/Bantech-Randon). 2012. *Alternative Technologies in Rigid Foam for Transportation. The Folle Conversion Case.* Advancing Ozone and Climate Protection Technologies: Next Steps Conference. July 20-21, 2012. Bangkok, Thailand. Summary available at http://www.unep.org/ccac/Portals/24183/docs/Bangkok%20Technology%20Conference%20-%20Report%20and%20Cover%20-%20FINAL.pdf.

Ecomate. 2012. *Cost Effective Blowing Agent for Polyurethane Foam Applications.* Advancing Ozone and Climate Protection Technologies: Next Steps Conference. July 20-21, 2012. Bangkok, Thailand.

FTOC. 2010. *2010 Rigid and Flexible Foams Report.* Available at: http://ozone.unep.org/teap/Reports/FTOC/FTOC-2010-Assessment-Report.pdf.

Honeywell. 2000. Comments of Honeywell Inc. on U.S. Environmental Protection Agency Proposed Listing of Certain HCFCs and Blends as "Unacceptable" Substitutes for HCFC-141b–65 Fed. Reg. 42653 (11 July 2000). Personal communication from Richard Ayers of Howrey, Simon, Arnold, and White to Anhar Karimjee of EPA on September 11, 2000. Available from EPA's Foams Docket A-200-18, Document IV-D-41.

Honeywell (Williams, D.). 2012a. *Solstice Blowing Agents Low Climate Impact, High Energy Efficiency.* Advancing Ozone and Climate Protection Technologies: Next Steps Conference. July 20–21, 2012. Bangkok, Thailand.

Honeywell. 2012b. *Honeywell Low Global Warming Technologies: One-Component Foam—HFO-1234ze. 2004–2012*. Available at: http://www51.honeywell.com/sm/lgwp-uk/applications-n2/one-component-foam-HFO-1234ze.html.

Technology and Economic Assessment Panel (TEAP). May 2012. Decision XXIII/0 Task Force Report: Additional Information on Alternatives to Ozone-Depleting Substance. Volume II.

United Nations Environment Programme (UNEP). 2010. *Guidance on the Process for Selecting Alternatives to HCFCs in Foams Sourcebook on Technology Options for Safeguarding the Ozone Layer and the Global Climate System.* Prepared by Caleb Management Services.

United Nations Environment Programme (UNEP). 2011a. *Project Proposal: China.* China HCFC Phase-out Management Plan. UNEP/OzL.Pro/ExCom/64/39. June 15, 2011. Available at: http://www.multilateralfund.org/MeetingsandDocuments/currentmeeting/64/English/1/6429.pdf.

United Nations Environment Programme (UNEP). 2011b. *Project Proposal: Mexico.* Mexico HCFC Phase-out Management Plan. UNEP/OzL.Pro/ExCom/64/39. June 17, 2011. Available at: http://www.multilateralfund.org/MeetingsandDocuments/currentmeeting/64/English/1/6439.pdf.

U.S. Environmental Protection Agency (USEPA). June 2006. *Global Mitigation of Non-CO_2 Greenhouse Gases*. U.S. EPA #430-R-06-005. Washington, DC: Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). October 30, 2009. *2009 Marginal Abatement Cost Curve Analysis for Reduction of HFCs in Traditional Ozone Depleting Substance (ODS) End-Use Applications: Draft Report.* Prepared by ICF International.

U.S. Environmental Protection Agency (USEPA). (2012a). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). August 10, 2012b. Protection of Stratospheric Ozone: Determination 27 for Significant New Alternatives Policy Program. *Federal Register.* Vol. 77, No. 155. http://www.gpo.gov/fdsys/pkg/FR-2012-08-10/pdf/2012-19688.pdf.

Whirlpool. August 15, 2012. Whirlpool Corporation and Honeywell Introduce Most Environmentally Responsible and Energy Efficient Insulation Available into U.S. Made Refrigerators. Available at: http://honeywell.com/News/Pages/Whirlpool-Corp-and-Honeywell-Introduce-Most-Environmentally-Responsible-and-Energy-Efficient-Insulation-Available-Refridge.aspx.

Williams, D. January 2013. Personal communication between Jenny Tanphanich, ICF International, and Dave Williams, Honeywell.

Williams, D.J., M.C. Bogdan, and P.B. Logsdon. 1999. *Optimizing Performance and Value: HFC-245fa and Blends of HFC-245fa for Insulating Foams.* Conference Proceedings from the Earth Technologies Forum TF 1999, pp. 290-302.

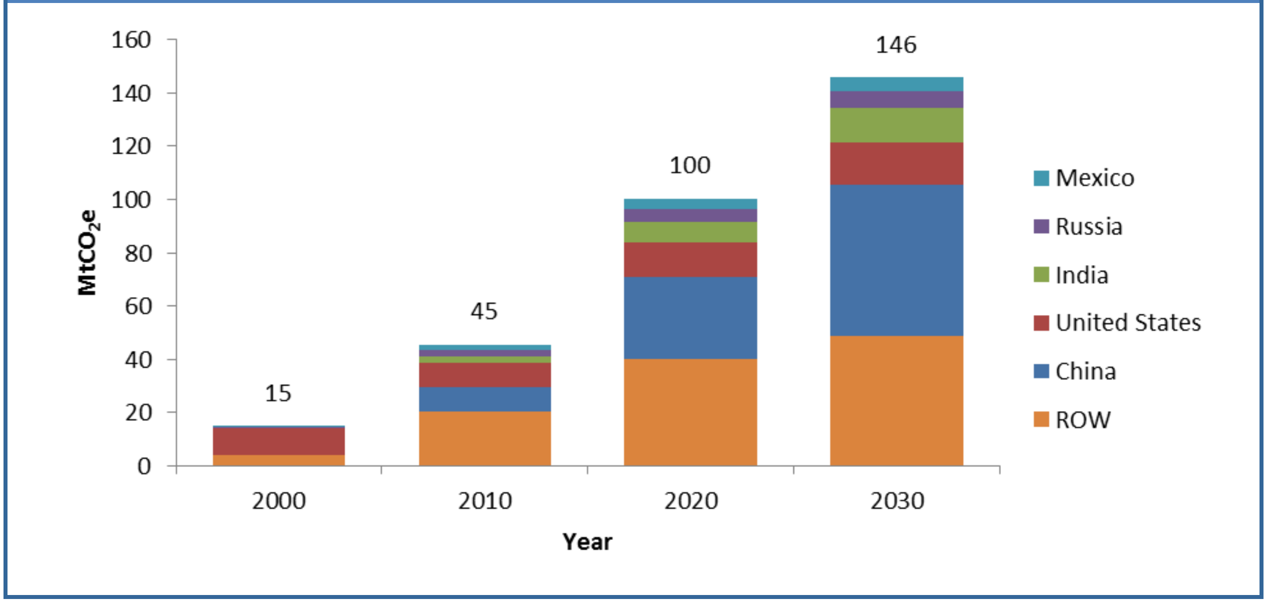
IV.5. HFC Emissions from Aerosol Product Use

IV.5.1 Sector Summary

Aerosol propellant formulations containing HFCs are used in a variety of consumer products, such as spray deodorants and hair sprays, and specialty aerosol uses, such as freeze spray and dust removal products. Additionally, aerosol propellants containing HFCs are used in pharmaceutical products, primarily metered dose inhalers (MDIs).

Global HFC emissions from the aerosols sector were estimated at roughly 45 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010 and are expected to climb to 146 $MtCO_2e$ by 2030 as shown in Figure 5-1. A majority of the growth is attributed to an increase in the consumption of HFCs for aerosol applications in developing countries.

Figure 5-1: HFC Emissions from Aerosol Product Use: 2000–2030 ($MtCO_2e$)

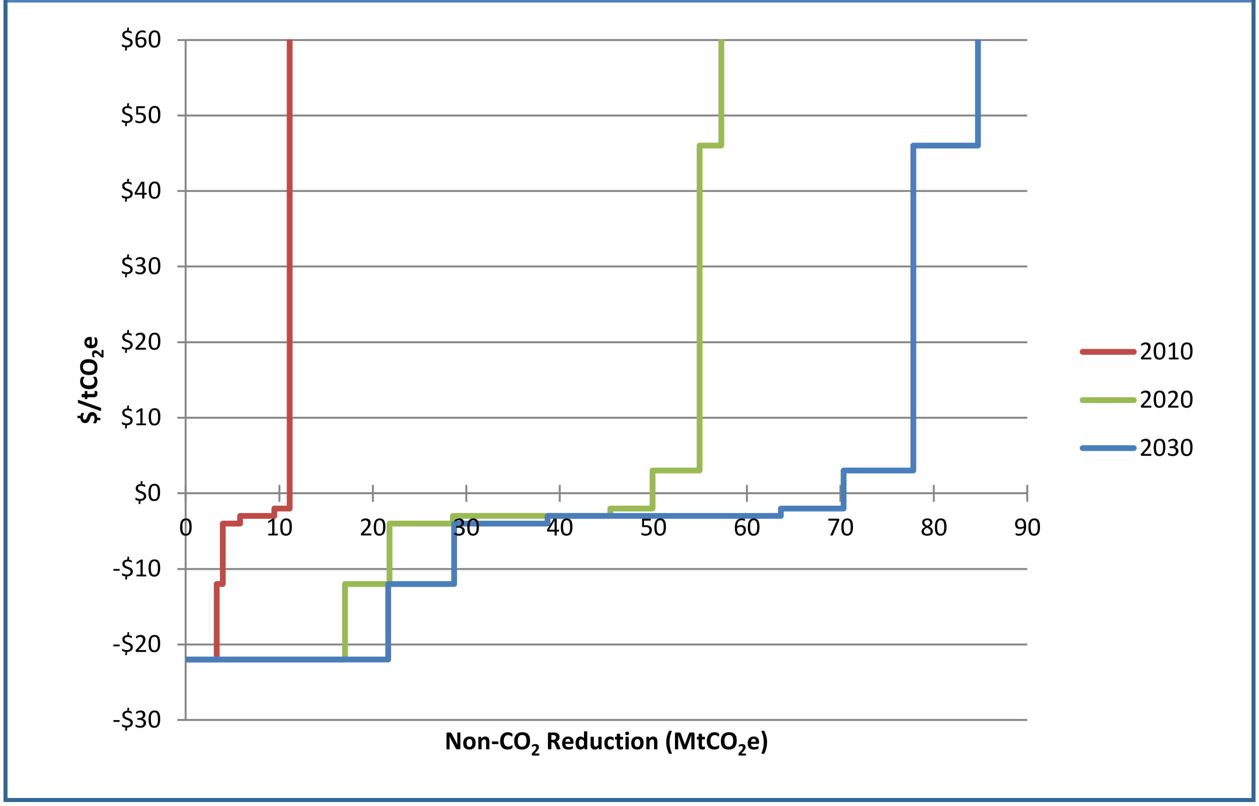


Source: USEPA, 2012.

A variety of abatement measures are available to reduce emissions. For consumer aerosol products, the options include transitioning to replacement propellants with very low global warming potentials (GWPs) and converting to a not-in-kind (NIK) alternative, such as a stick, roller, or finger/trigger pumps. Dry powder inhaler (DPI) technology is considered in this analysis as a replacement measure for MDIs.

The global abatement potential from aerosols is equal to approximately 66% of total annual emissions from the aerosols sector and 5% of total annual emissions from all sectors that use ODS substitutes. Potentially, nearly 100% abatement is possible for consumer aerosol products; whereas abatement is more limited for MDIs due to medical reasons (e.g., DPIs are not suitable for cases of severe asthma or for young children). Marginal abatement cost (MAC) curve results are presented in Figure 5-2. Maximum abatement potential in the aerosols sector is 97 $MtCO_2e$ in 2030. There are 70 $MtCO_2e$ of emissions reductions that are cost-effective at currently projected energy prices for 2030.

Figure 5-2: Global Abatement Potential in Aerosol Product Use: 2010, 2020, and 2030



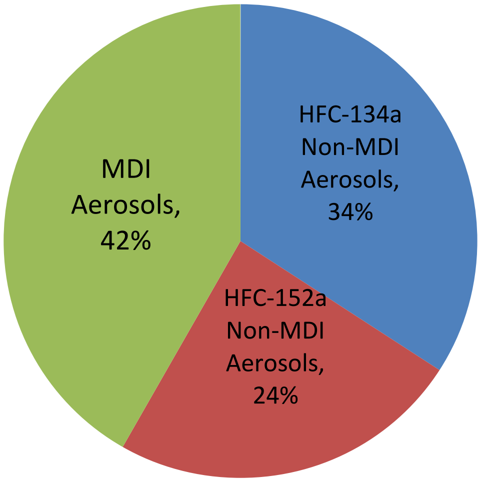
IV.5.2 Emissions from Aerosol Product Use

Aerosol propellants are completely emitted during product use. This analysis estimates emissions from consumer aerosol products, such as spray deodorants and hair sprays, and specialty aerosol uses, such as freeze spray and dust removal products, and, separately, emissions from MDIs. HFC-134a has been introduced as an alternative propellant to chlorofluorocarbons (CFCs) in both MDIs and consumer aerosol products; in addition, HFC-227ea is used in MDIs and HFC-152a is used in consumer aerosol applications. This analysis characterizes these three categories, for the purposes of evaluating the cost of reducing HFC emissions, as follows:

- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-134a aerosol propellant charge of two ounces;
- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-152a aerosol propellant charge of two ounces; and
- a single 200-dose MDI aerosol unit with a charge size of 15 grams that uses HFC-134a propellant.

The relative shares of these applications are displayed in Figure 5-3.

Figure 5-3: Global HFC Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



IV.5.2.1 Activity Data or Important Sectoral or Regional Trends

HFC emissions from the aerosols sector represented 10% of total ODS substitute emissions in 2010. Emissions were estimated based on estimated market size and charge size of aerosol products in the United States, which was then proxied to other regions based on each country's gross domestic product. Growth in aerosol products correlates with economic growth, and because of the global, commoditized nature of this sector, there are no significant regional differences in the aerosol products themselves. Aerosols are fully emissive, and the HFCs contained within the aerosol are assumed to be emitted within a year of consumption. Many non-MDI aerosols already use alternative propellants, either hydrocarbons (HCs) or manual pump mechanisms; thus, the baseline adoption of the reduction technologies is quite high in the market.

IV.5.2.2 Emission Estimates and Related Assumptions

Global emissions of HFCs from the aerosols sector were estimated to be 45 $MtCO_2e$ in 2010, growing to 146 $MtCO_2e$ in 2030, as shown in Table 5-1. The majority of emissions are HFC-134a, with lesser amounts of HFC-152a and HFC-227ea. Emissions are projected to grow significantly as developing countries' economies grow and demand for consumer aerosols grows. Emissions were estimated using USEPA's Vintaging Model and assumptions about initial market size of the sector, the specific transitions away from CFCs in terms of timing and alternative propellant used, charge sizes, and leak rates.

IV.5.3 Abatement Measures and Engineering Cost Analysis

A total of five abatement options were identified for the aerosols sector. For consumer aerosol products, the options are transitioning to a replacement propellant—including HCs, HFO-1234ze, and HFC-152a (for those products containing HFC-134a)—and converting to a NIK alternative, such as a stick, roller, or finger/trigger pump. Costs are analyzed by looking at a model facility that uses HFC to fill 10 million aerosol cans a year. For MDIs, the abatement measure examined by this analysis is further use of dry powder inhaler technology where suitable for the patient. Costs are analyzed based on a single DPI

Table 5-1: Projected Baseline Emissions from Aerosol Product Use: 2010-2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	9.4	23.0	31.2	42.2	56.9	9.4%
United States	8.9	11.9	13.0	14.2	15.6	2.8%
India	2.4	5.7	7.6	9.9	13.0	8.8%
Russia	2.6	3.9	4.6	5.4	6.2	4.4%
Mexico	1.9	3.7	4.2	4.8	5.4	5.3%
Rest of Regions						
Africa	3.0	6.3	7.6	8.9	10.4	6.3%
Central and South America	1.3	2.6	3.0	3.5	4.0	5.7%
Middle East	1.8	3.7	4.4	5.1	6.0	6.2%
Europe	9.5	14.6	15.1	15.6	16.0	2.6%
Eurasia	0.4	0.5	0.6	0.7	0.8	4.4%
Asia	4.0	7.7	8.7	9.9	11.2	5.3%
North America	0.2	0.4	0.4	0.5	0.5	4.6%
World Total	**45.5**	**84.2**	**100.4**	**120.7**	**145.8**	**6.0%**

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA), 2011

compared to a single MDI, with estimated cost data that incorporates the cost associated with avoided use of HFC-134a propellant, the increase in the cost of DPI treatment, the cost to market the new treatment, and the cost to retrain the patients in using the DPI (Ecofys, 2000; Enviros, 2000). Table 5-2 summarizes the applicability of each abatement option to the aerosol emission categories. The subsequent subsections describe each abatement option in more detail.

IV.5.3.1 Hydrocarbons

This option replaces HFC-134a or HFC-152a in non-MDI aerosols with an HC-based propellant. HC aerosol propellants are usually mixtures of propane, butane, and isobutane.[1] Their primary advantage lies in their affordability; the price of HC propellants which range from one-third to one-half that of HFCs. The main disadvantages of HC aerosol propellants are flammability concerns and, because they are volatile organic compounds (VOCs), their contribution to ground-level ozone and smog. Despite these concerns, HC aerosol propellants already hold a sizable share of the market and may be acceptable for additional applications.

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[1] For calculation purposes, a GWP of 3.48 is used based on an average of the GWP of propane (GWP=3.3) and isobutane (GWP=3.65).

Table 5-2: Aerosol Product Use Abatement Options

	Reduction Efficiency			
Abatement Option	Consumer Aerosol Facility/ HFC 134a	Consumer Aerosol Facility/ HFC 152a	Metered Dose Inhaler	Applicability
Consumer Aerosol Products				
Hydrocarbon	99.7%	97.5%	NA	Consumer aerosol facility/HFC-134a/HFC-152a
Not-in-kind	100%	100%	NA	Consumer aerosol facility/HFC-134a/HFC-152a
HFO-1234ze	99.5%	95.7%	NA	Consumer aerosol facility/HFC-134a/HFC-152a
HFC-134a to HFC-152a	89.2%			Consumer aerosol facility/HFC-134a
Pharmaceutical Aerosol Products (MDIs)				
Dry powder inhalers	NA	NA	100%	Metered dose inhaler

Costs of converting filling facilities to accept HC propellants can range from $10,000 to potentially as high as $1.2 million; the one-time cost varies based on the need for investments in new equipment and the need to relocate to regions where the use of HCs is considered safe (Nardini, 2002). To accommodate any flammable propellant, a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system (Techspray, 2008; MicroCare, 2008). According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008). Given that HCs (estimated at $1/lb) are lower cost than HFC-134a or HFC-152a (estimated at $3/lb and $2/lb, respectively), the adoption of this abatement measure is expected to result in an annual savings associated with gas purchases, ranging from $1 million to nearly $3 million.

IV.5.3.2 Not-in-Kind

NIK aerosol devices include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These systems often prove to be a better and more cost-effective option than HFC-propelled aerosols, particularly in areas where a unique HFC property is not specifically needed. Because all of the HFC (either HFC-134a or HFC-152a) contained in the aerosol can is replaced with a device that does not use any GHGs, the reduction efficiency of this option is 100%.

Significant variability exists in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This variability is attributable to the wide range of potential aerosol and NIK product types. A one-time cost to make the conversion is estimated at $250,000; additionally, annual costs of $500,000 are estimated to address higher material costs of the particular sticks, rollers, and pumps being used (UNEP, 1999). An annual savings is expected, ranging from $2.3 million to $4.1 million, as a result of eliminating the need for a HFC propellant.

IV.5.3.3 HFO-1234ze

HFO-1234ze has potential application both as a propellant and also as the active ingredient in aerosol dusters. HFO-1234ze is nonflammable (at room temperature) and has physical properties that are very similar to both the HFC-134a and HFC-152a. Hence, it may be used as a 'drop-in' replacement for HFC propellants (MicroCare, 2011). The manufacturer of this chemical indicates that Europe and Japan have already begun to adopt HFO-1234ze, while interest is also rising in the United States because of awareness of environmental sustainability (Honeywell, 2011a). A number of dusters using HFO-1234ze are available today (Amazon, 2013; ITW Chemtronics, 2013; Miller Stephenson, 2013; Stanley Supply and Services, 2013). A large scale production facility is being built in the United States with an expected production of HFO-1234ze in late 2013 (Honeywell, 2011b). In the absence of regulations, adoption in Europe and Japan is expected to grow continuously at a moderate rate (reaching a maximum of 15% to 20% of today's HFC volume); therefore, this option is expected to penetrate up to 15% of the non-MDI HFC-134a market and up to 20% of the non-MDI HFC-152a market. In the United States, adoption of HFO-1234ze is expected to follow a similar path, but with a later start. In developing countries, no interest in HFO-1234ze is expected in the foreseeable future because of inexpensive options that are the preferred solutions today.

For this analysis, a one-time cost of roughly $500,000 is assumed because of the need for bulk storage. According to MicroCare (2011), although it is possible to use one ton cylinders and avoid the costs of adding bulk storage, using ton cylinders is inefficient and adds to the unit cost of the HFO material. Therefore, any facility using this material would almost certainly need to use bulk storage. This is likely a conservative (high) one-time cost estimate, considering it is about the same capital cost considered in the next section for a flammable propellant, whereas HFO-1234ze(E) is not flammable at room temperatures. Because HFO-1234ze has a higher cost than the other HFCs (i.e., HFC-134a and HFC-152a), a facility making the transition would incur a higher annual cost when adopting this propellant.

IV.5.3.4 HFC-134a to HFC-152a

This abatement measure examines replacing HFC-134a (with a GWP of 1,300) with HFC-152a (with a GWP of 140). HFC-134a is assumed to represent 58% of non-MDI aerosols; therefore, this abatement option is only applicable to 58% of the non-MDI aerosol model facilities. HFC-134a is the primary nonflammable propellant in certain industrial products. HFC-152a possesses only moderate flammability hazards and might, therefore, be acceptable for some applications that use HFC-134a, but it may present problems for other applications.

Costs of converting filling facilities to accept HFC-152a may range from $500,000 to $600,000, (Techspray, 2008; MicroCare, 2008). To accommodate HFC-152a (or any flammable propellant), a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system (Techspray, 2008). Aside from the costs associated with building a storage house, no other significant expenses would be incurred. According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008). The lower cost of HFC-152a (compared with HFC-134a) results in an annual savings associated with gas purchases, estimated at $1.8 million for a typical aerosol filling facility.

IV.5.3.5 Dry Powder Inhalers

Dry powder inhalers (DPIs) are a viable abatement measure for most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder, that contains the drug agent, is contained in the DPI, a non-pressurized delivery system, and is inhaled and deposited in the lungs. They are suitable only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates. Other issues that doctors and patients consider when choosing a treatment device include the patient's manual dexterity, ability to adapt to a new device, and perception of the effectiveness of the medicine and taste of any added ingredients. Ultimately, these and other critical patient care issues must be assessed by the doctor and patient in choosing whether a DPI, MDI or other type of therapy is most appropriate (Price et al., 2004; UNEP, 2010). Where feasible, DPIs—which do not contain GHGs—could be used in lieu of HFC-containing MDIs; hence, the reduction efficiency of this option is 100%.

Costs incurred with using DPIs include the increased cost of DPI treatment, the cost to market the new treatment, and the cost to retrain patients to use the DPI (Enviros, 2000). The cost of research and development of new drugs and delivery mechanisms can also be significant; however, as both MDIs and DPIs are available to the market today, and due to a lack of specific cost information, such expenses are not considered in this analysis.

IV.5.3.6 Engineering Cost Data Summary

Table 5-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price. For more detailed costs information see Appendix G.

Table 5-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility/Emission Type	Project Lifetime (years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
Consumer Aerosol Products						
HCs	Consumer aerosol/HFC-134a	10	$325,000	$2,800,000	—	735,130
	Consumer aerosol/HFC-152a			$1,000,000		77,410
Not-in-Kind	Consumer aerosol/HFC-134a	10	$250,000	$4,100,000	$500,000	737,100
	Consumer aerosol/HFC-152a			$2,300,000		79,380
HFO-1234ze	Consumer aerosol/HFC-134a	10	$500,000	—	$1,400,000	730,312
	Consumer aerosol/HFC-152a				$3,200,000	72,722
HFC-134a to	Consumer aerosol/HFC-134a	10	$500,000	$1,800,000	—	586,889
Pharmaceutical Aerosol Products (MDIs)						
DPIs	Metered dose inhaler	10	—	—	$700,000	1,300

IV.5.4 Marginal Abatement Costs Analysis

IV.5.4.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

IV.5.4.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Market penetration rates vary over time as systems are upgraded in the future. Table 5-4 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of each option.

Table 5-4: Technical Effectiveness Summary

Abatement Option	Technical Applicability	Market Penetration Rate (2030)	Reduction Efficiency	Technical Effectiveness (2030)
Consumer Aerosol Products				
HFC-134a to HC	58%	50%	99.7%	29.0%
HFC-134a to NIK	58%	20%	100.0%	11.6%
HFC-134a to HFO-1234ze	58%	15%	99.5%	8.7%
HFC-134a to HFC-152a	58%	15%	89.2%	7.8%
HFC-152a to HC	42%	20%	97.5%	8.2%
HFC-152a to NIK	42%	60%	100.0%	25.1%
HFC-152a to HFO-1234ze	42%	20%	95.7%	8.0%
Pharmaceutical Aerosol Products (MDIs)				
DPI	100%	20%	100.0%	20.0%

[a] Technical effectiveness (TE) is the product of TA*MP*RE.

IV.5.4.3 Estimating Abatement Project Costs and Benefits

Table 5-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities and are used in the calculation that solves for the break-even price that sets each project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for different facilities.

The break-even prices presented in Table 5-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section 5.4.4.

Table 5-5: Example Break-Even Prices for Abatement Measures in Aerosol Product Use

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Consumer Aerosol Products					
HFC-134a to HC	735,130	0.1	−3.8	0.0	−3.7
HFC-134a to NIK	737,100	0.1	−4.9	0.0	−4.8
HFC-134a to HFO-1234ze	730,312	0.2	1.9	0.0	2.1
HFC-134a to HFC-152a	586,889	0.2	−3.1	0.1	−2.9
HFC-152a to HC	77,410	1.1	−12.9	0.3	−12.1
HFC-152a to NIK	79,380	0.9	−22.7	0.2	−22.0
HFC-152a to HFO-1234ze	72,722	1.9	44.0	0.5	45.4
Pharmaceutical Aerosol Products (MDIs)					
DPI	1,300	0.0	538.5	0.0	538.5

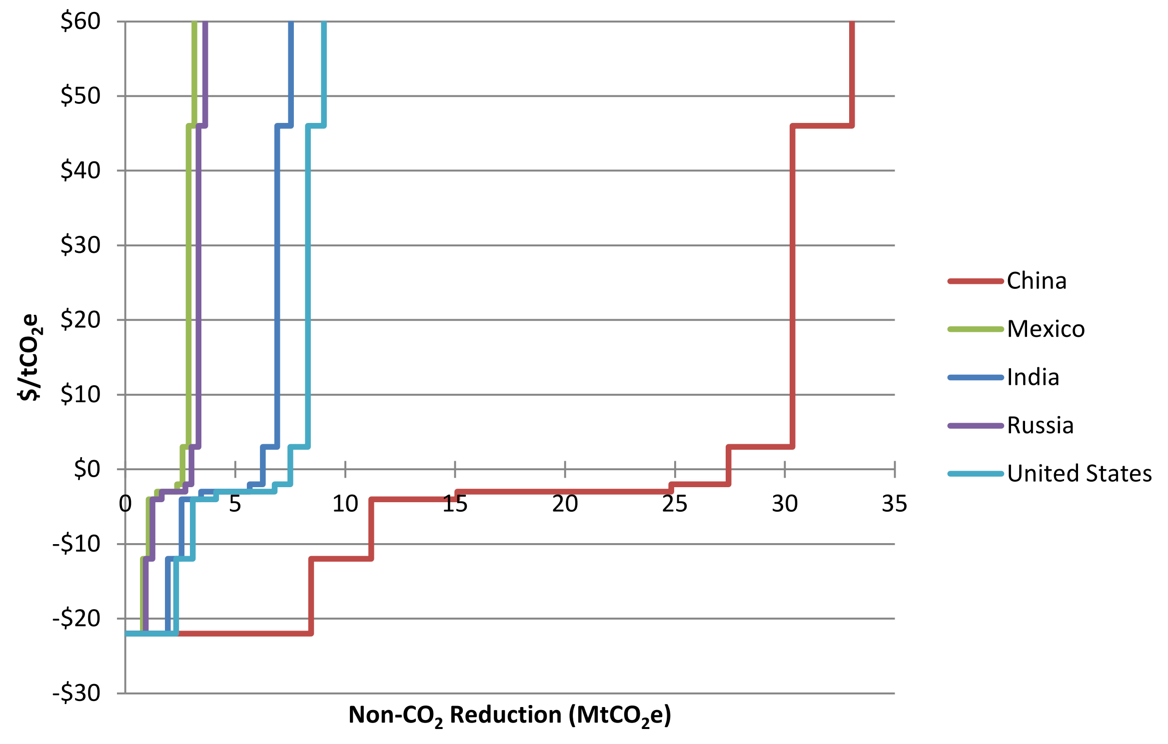
IV.5.4.4 MAC Analysis Results

Global abatement potentials in 2020 and 2030 are 66 and 97 $MtCO_2e$, respectively. There are 70 $MtCO_2e$ of reductions in projected baseline emissions in 2030 resulting from implementing currently available technologies that are cost-effective at projected prices. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to producers of aerosols, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 5-6 and Figure 5-4 by major country and regional grouping at select break-even prices in 2030.

Table 5-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($/$tCO_2e$)										
Country/Region	**−10**	**−5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
China	11.2	11.2	27.4	30.4	30.4	30.4	30.4	30.4	33.0	33.0	37.7
India	2.5	2.5	6.2	6.9	6.9	6.9	6.9	6.9	7.5	7.5	8.6
Mexico	1.1	1.1	2.6	2.9	2.9	2.9	2.9	2.9	3.1	3.1	3.6
Russia	1.2	1.2	3.0	3.3	3.3	3.3	3.3	3.3	3.6	3.6	4.1
United States	3.1	3.1	7.5	8.3	8.3	8.3	8.3	8.3	9.0	9.0	10.3
Rest of Region											
Africa	2.0	2.0	5.0	5.5	5.5	5.5	5.5	5.5	6.0	6.0	6.9
Central and South America	0.8	0.8	1.9	2.1	2.1	2.1	2.1	2.1	2.3	2.3	2.6
Middle East	1.2	1.2	2.9	3.2	3.2	3.2	3.2	3.2	3.5	3.5	4.0
Europe	3.1	3.1	7.7	8.5	8.5	8.5	8.5	8.5	9.3	9.3	10.6
Eurasia	0.2	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.6
Asia	2.2	2.2	5.4	6.0	6.0	6.0	6.0	6.0	6.5	6.5	7.4
North America	0.1	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**28.7**	**28.7**	**70.3**	**77.8**	**77.8**	**77.8**	**77.8**	**77.8**	**84.7**	**84.7**	**96.7**

Figure 5-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



IV.5.5 Uncertainties and Limitations

The significant areas of uncertainty in this analysis are in how costs for these mitigation technologies may vary internationally. The analysis is currently limited in the lack of detail on cost assumptions, which may not accurately represent the transition costs regionally. Additionally, the cost assumptions for the transition to DPIs are based on a study released in 2000, which may not reflect the latest technical and economic parameters. Finally, the general methodology used here projects increasing use of HFC aerosols based on historical growth and expanding GDPs. Some market sectors may not expand that quickly; for instance, HFC growth in MDIs is projected to grow from current use of 4,000 metric tons globally to 7,000-10,500 metric tons in 2015 (UNEP, 2010).

References

Amazon, 2013. Falcon DPSGRN Dust-Off ECO Duster, 5 oz Canister (Case of 12). Obtained August 21, 2013. Available at: http://www.amazon.com/industrial-scientific/dp/B009L9A2X6.

Ecofys. 2000. *Abatement of Emissions of Other Greenhouse Gases: Engineered Chemicals*. Prepared for the International Energy Agency Greenhouse Gas Research and Design Programme. Ecofys.

Enviros March. 2000. *Study on the Use of HFCs for Metered Dose Inhalers in the European Union*. Commissioned by the International Pharmaceutical Aerosol Consortium (IPAC). Enviros March.

Honeywell. November 2011a. E-mail communication between Alberto Malerba (Honeywell) and Pamela Mathis (ICF International).

Honeywell. July 2011b. Press Release, "Honeywell To Invest $33 Million In Louisiana Facility." Obtained in February 2013 at: http://honeywell.com/News/Pages/Honeywell-To-Invest-$33-Million-In-Louisiana-Facility.aspx.

ITW Chemtronics, 2013. Typhoon Blast™ Duster. Obtained August 21, 2013. Available at: http://www.chemtronics.com/products/product.asp?id=598.

Javadi, M.S., R. Sondergaard, O.J. Nielsen, M.D. Hurley, and T.J. Wallington. 2008. "Atmospheric Chemistry of Trans-CF3CH=CHF: Products and Mechanisms of Hydroxyl Radical and Chlorine Atom Initiated Oxidation." *Atmospheric Chemistry and Physics* 8:1069-1088. Available at: http://www.atmos-chem-phys-discuss.net/8/1069/2008/acpd-8-1069-2008.pdf.

MicroCare Corporation. August 2008. Personal communication between Jay Tourigny, MicroCare Corporation, and Emily Herzog, ICF International.

MicroCare Corporation. November 2011. E-mail communication between Jay Tourigny, MicroCare Corporation, and Emily Herzog, ICF International.

Miller-Stephenson, 2013. Aero-Duster® product information. Obtained August 21, 2013. Available at: http://www.miller-stephenson.com/assets/1/Store%20Item/MS-222L.pdf.

Nardini, Geno. May 2002. Personal communication between Geno Nardini and Iliriana Mushkolaj of ICF Consulting.

Price, D., E. Valovirta, and J. Fischer. 2004. "The Importance of Preserving Choice in Inhalation Therapy: The CFC Transition and Beyond." *Journal of Drug Assessment* 7:45-61.

Stanley Supply & Services, 2013. Techspray Renew 1580-10S Eco-Duster, 10oz. Obtained August 21, 2013. Available at: http://www.stanleysupplyservices.com/techspray-renew-1580-10s-eco-duster-10oz/p/477-260.

TechSpray. August 2008. Personal communication between Steve Cook of TechSpray and Emily Herzog of ICF International.

United Nations Environment Programme (UNEP). 1999. *1998 Report of the Solvents, Coatings, and Adhesives Technical Options Committee (STOC): 1998 Assessment*. Nairobi, Kenya: UNEP Ozone Secretariat.

United Nations Environment Programme (UNEP). 2010. *Report of the UNEP Medical Technical Options Committee*: *2010 Assessment.* Nairobi, Kenya: UNEP Ozone Secretariat.

U.S. Environmental Protection Agency (USEPA). 2001. U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities for Reductions. EPA #000-F-97-000. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). June 2011. *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions.* U.S. EPA #000-F-97-000. Washington, DC: Office of Air and Radiation, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

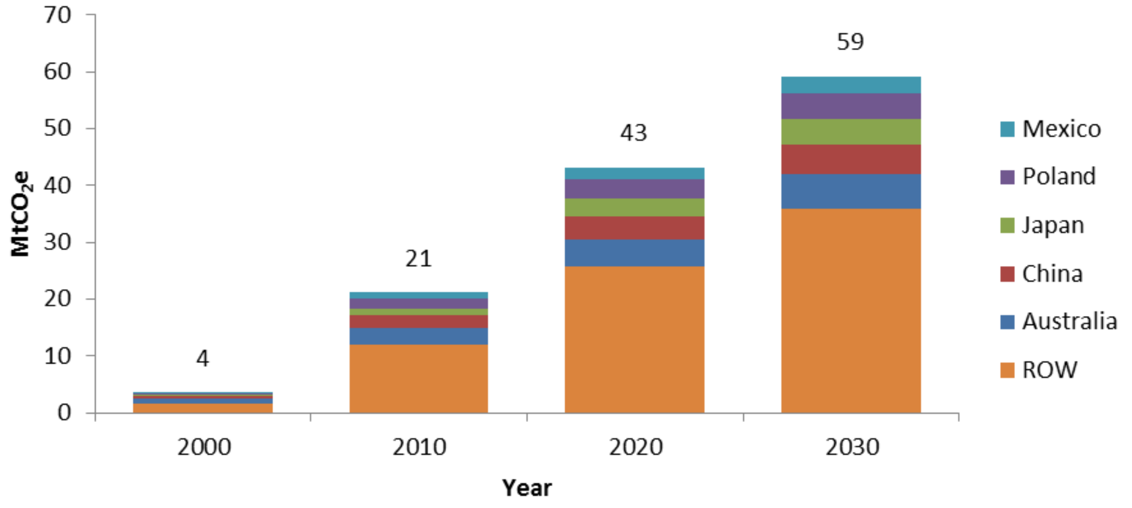
X-rates.com. 2006. Available at: www.x-rates.com. Accessed January 2006.

IV.6. HFC and PFC Emissions from Fire Protection

IV.6.1 Sector Summary

The fire protection sector emits hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) from the use of total flooding fire protection systems in fire suppression. This sector also includes portable (hand-held) fire extinguishers. Greenhouse gas emissions from the fire protection sector (excluding halons and hydrochlorofluorocarbons) were estimated at roughly 21 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010, as shown in Figure 6-1. By 2030, emissions from this sector are expected to reach over 59 $MtCO_2e$. A majority of the growth will result from increased use of HFCs in developing countries.

Figure 6-1: HFC and PFC Emissions from Fire Protection: 2000–2030 ($MtCO_2e$)

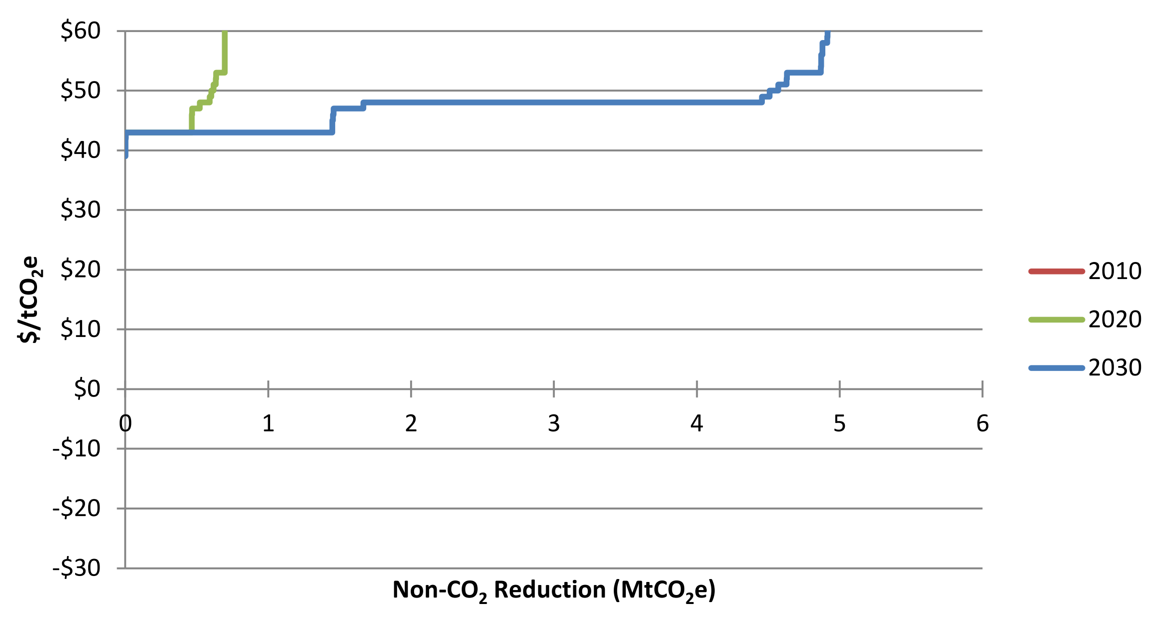


Source: USEPA, 2012.

This analysis reviews options to reduce emissions from the fire protection sector by using extinguishing agents with low global warming potential (GWP) in lieu of HFCs/PFCs in new total flooding equipment, specifically, replacement of the HFC with inert gas, water mist, or the agent FK-5-1-12.

The global abatement potential from the fire protection options reviewed is equal to approximately 11% of total annual emissions from the fire protection sector and 0.3% of total annual emissions from all sectors that use ODS substitutes. The options identified to abate emissions in the fire protection sector completely replace the fluorinated fire protection agents, however, they are assumed to only be implemented when new systems are built. Thus, their effectiveness at reducing emissions will increase over time as new systems are built, but it will take many years before the existing stock would be replaced. Marginal abatement cost (MAC) curve results are presented in Figure 6-2. Maximum abatement potential in the fire extinguishing sector is 6.4 $MtCO_2e$ in 2030. There are no emission reductions that are cost-effective at prices estimated in this analysis. No reductions are available in 2010 as a result of the assumption that the available technologies are only used for new installations and did not start to penetrate the market until 2011.

Figure 6-2: Global Abatement Potential in Fire Protection: 2010, 2020, and 2030



IV.6.2 Emissions from Fire Protection

Emissions from fire protection equipment occur from equipment leakage, accidental discharges, and use during fire extinguishing. In general, fire protection systems have very low leak rates, except when discharged during a fire event. The majority of emissions associated with fire extinguishing come from the equipment's use in the total flooding market (see Figure 6-3). Portable extinguishers—used most frequently in offices, manufacturing and retail facilities, aerospace/marine applications, and homes—also use HFCs, but such use has been limited (Wickham, 2003).

For the purpose of this analysis, we considered the sector's two types of fire protection systems—(1) portable fire extinguishers (i.e., streaming applications) and (2) total flooding applications. Typical portable extinguishers contain 1.3 kg of HFC-236fa, which is assumed to be extinguished with a frequency such that emissions are 3.5%/year. The typical flooding application uses HFC-227ea; because discharge is infrequent, emissions are 2% per year.

For modeling purposes, data typical for facilities in the United States are used. Certain cost assumptions, such as capital and electricity costs, are adjusted for developing countries.[1] Otherwise, it is assumed that the costs and reductions achieved in the modeled facilities could be scaled and would be representative of the costs and reductions in other regions.

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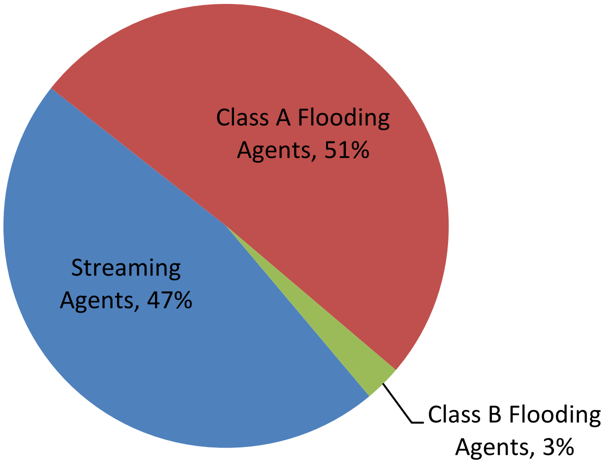
[1] In developing countries, it is assumed that capital costs are 10% higher and electricity costs are two-thirds higher relative to those in the United States.

Figure 6-3: Global HFC and PFC Emissions in 2020 (% of GWP-Weighted Emissions)



IV.6.2.1 Activity Data or Important Sectoral or Regional Trends

The key activity data for fire extinguishing emissions is the consumption of the fire extinguishing agent. Fire extinguishing agent consumption is assumed to occur in all countries and to scale with a country's gross domestic product (GDP); in addition, because there are no regional differences in emission rates, emissions also scale with GDP.

Globally, HFC and PFC emissions from fire protection have been growing because of the phaseout of halon under the Montreal Protocol. Because developed countries phased out the use of halon earlier than developing countries, the growth in global emissions for the past decade has been driven by emissions from developed countries. However, because of the high GDP growth in developing countries, it is anticipated that emissions will grow more quickly from developing countries in the future.

In total flooding applications that require "clean agents,"[2] most developed countries have primarily adopted HFCs as a replacement for Halon 1301, which is being phased out under the Montreal Protocol. In developing countries, the adoption of HFCs in this application has been delayed by the slower phaseout of halon but will increase over time.

IV.6.2.2 Emission Estimates and Related Assumptions

Global emissions from fire protection are currently estimated to be 21 $MtCO_2e$ and are projected to grow to 43 $MtCO_2e$ in 2020. Growth in emissions is driven by GDP. The emissions assume a constant

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[2] "Clean agents" are gaseous extinguishing agents that are electrically nonconductive and leave no residue.

annual release rate of 3.5% and 2% of consumption for streaming and flooding, respectively.[3] Consumption was modeled using USEPA's Vintaging Model. Emissions for major countries and regions are presented in Table 6-1.

Table 6-1: Projected Baseline Emissions from Fire Protection: 2010 to 2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
Australia	2.9	4.0	4.8	5.4	6.0	3.8%
China	2.2	3.2	4.0	4.6	5.2	4.3%
Japan	1.3	2.2	3.1	4.0	4.7	6.7%
Poland	1.7	2.5	3.3	4.0	4.5	5.0%
Mexico	1.1	1.7	2.2	2.6	3.0	5.1%
Rest of Region						
Africa	1.3	1.9	2.4	2.7	3.0	4.5%
Latin America	1.6	2.5	3.3	3.9	4.5	5.1%
Middle East	1.8	2.6	3.3	3.8	4.3	4.5%
Europe	3.9	6.6	9.8	12.4	13.9	6.6%
Eurasia	0.8	1.5	2.4	3.2	3.8	8.5%
Asia	1.8	2.6	3.2	3.6	4.1	4.2%
North America	0.9	1.2	1.6	2.0	2.3	4.9%
World Total	**21.2**	**32.5**	**43.2**	**52.2**	**59.3**	**5.3%**

[a] CAGR = Compound Annual Growth Rate
Source: U.S. Environmental Protection Agency (USEPA), 2012.

IV.6.3 Abatement Measures and Engineering Cost Analysis

The alternatives to HFCs/PFCs in total flooding applications can be categorized as in-kind gaseous agent alternatives (i.e., CO_2, inert gases, fluorinated ketones) and "not-in-kind" alternatives (i.e., dispersed and condensed aerosol extinguishing systems, water sprinklers, water mist, foam, or inert gas generators). Already, climate-friendly clean agents and new not-in-kind alternative technologies have been introduced to the market.

This analysis reviews options to reduce emissions from the fire protection sector by using zero-GWP or low-GWP extinguishing agents in lieu of HFCs/PFCs in new total flooding equipment. Specifically, this analysis assesses alternative agents used in newly built total flooding systems to protect against Class A

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[3] In general, fire protection systems would be expected to have very low leak rates, except when discharged during a fire event. For modeling purposes, however, total flooding systems are assumed to have an average annual leak rate of 2% (see Appendix H to this chapter).

surface fire hazards[4] and newly built total flooding systems to protect against Class B fuel hazards[5] in large (≥ 3,000 m^3) marine applications. All costs are presented in 2010 dollars based on the Consumer Price Index (U.S. Department of Labor, 2011).

Facilities/emissions for which no abatement options are considered in this analysis include existing total flooding systems (used to protect against all fire hazards) and all new and existing portable extinguishers. Existing flooding systems were not assessed because alternative fire protection agents require larger space requirements, rendering system retrofit costs highly dependent on the particular facility and possibly cost-prohibitive. Portable extinguishers were not assessed because emissions from this source are small, and climate-friendly alternatives are already assumed to be used widely in the baseline.

The analyzed facilities are assessed on a per-cubic meter of protected space basis, assuming an average emission rate of 2% per year. Specifically, for Class A surface fire hazards, an average of 0.633 kg of HFC-227ea is needed to protect each cubic meter of protected space; while 0.630 kg is required for large Class B fire hazards (Wickham, 2003).

Three abatement options were considered for this analysis: in new Class A total flooding systems, replacement with either FK-5-1-12 or inert gas, and in new Class B total flooding systems, replacement with water mist. Each of these options is described below in Table 6-2.

Table 6-2: Fire Protection Abatement Options

Abatement Option	Applicable System Types	Reduction Efficiency
FK-5-1-12	New Class A total flooding	100%
Inert gas	New Class A total flooding	100%
Water mist	New Class B total flooding	100%

IV.6.3.1 FK-5-1-12 in New Class A Total Flooding Applications

FK-5-1-12-mmy2 (also known as 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, and commonly referred to as FK-5-1-12) is a fluorinated ketone with an atmospheric lifetime of five days and a 100-year GWP of approximately one (Kidde Fire Protection, 2011). This option examines use of FK-5-1-12 in total flooding systems. The option is applicable in new Class A total flooding applications, replacing HFCs (primarily HFC-227ea). Class A total flooding application end-uses represent an estimated 95% of

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[4] This analysis assumes that Class A fire hazards represent an estimated 95% of the total flooding sector. This estimate is based on Wickham (2002), who estimates that over 90% of the Halon 1301 systems ever installed in the United States were designed to protect against hazards where the anticipated fire type was primarily Class A in nature and approximately 10% of the U.S. applications served by Halon 1301 had hazardous materials of the Class B type. However, because much of the former Halon 1301 Class B applications have been replaced by non-HFC alternatives (e.g., carbon dioxide), this analysis assumes that only 5% of HFC emissions from the total flooding sector are from Class B applications and the remaining 95% are from Class A applications.

[5] This analysis assumes that Class B fire hazards represent an estimated 5% of the total flooding sector, based on Wickham (2002) (as explained in previous footnote).

the total flooding sector; [6] the additional adoption of FK-5-1-12 is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are estimated at $9.49 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs are estimated at $0.03 per cubic meter of protected space for additional electricity needed to heat/cool the additional space as well as the higher agent replacement costs.

IV.6.3.2 Inert Gas Systems in New Class A Total Flooding Applications

Inert gas systems extinguish fires using argon, nitrogen, or a blend of the two, sometimes incorporating CO_2 as a third component (UNEP, 2001). Inert gas systems provide an equivalent level of both fire protection and life safety/health protection in most Class A (ordinary combustible) fire hazards, including electronics and telecommunications applications. Limitations of the inert gas systems include a slower discharge time than that of HFC systems—60 seconds or more compared with 10 to 15 seconds (Kucnerowicz-Polak, 2002)—and a larger volume of agent needed than in HFC systems to extinguish fires. The weight-support structures and space needed for additional steel cylinders of gas may prohibit the retrofit of many existing HFC systems, such as those on small ships and in other applications where the system infrastructure is fixed.

This technology option is assumed to be applicable in new Class A application end uses, replacing HFCs (primarily HFC-227ea). Class A total flooding application end uses represent an estimated 95% of the total flooding sector;[7] the additional adoption of inert gas systems is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are $11.16 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs in developed countries are estimated at $0.17/cubic meter of protected space for additional electricity needed to heat/cool the additional space; the electricity costs are assumed to be two-thirds greater in developing countries. Annual costs are offset by annual savings associated with lower agent replacement costs, estimated at $0.28/cubic meter of protected space.

IV.6.3.3 Water Mist Systems in New Class B Total Flooding Applications

Water mist systems use relatively small droplet sprays under low, medium, or high pressure to extinguish fires. These systems use specially designed nozzles to produce much smaller droplets than are produced by traditional water-spray systems or conventional sprinklers, so they use less water to extinguish a fire (UNEP, 2001; Wickham, 2002). However, some barriers have impeded broad use of water mist systems. First, these systems may be cost prohibitive in small spaces and have not proven

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[6] See footnote 4.

[7] See footnote 4.

effective in extinguishing small fires in large volume spaces (≥ 3,000 m^3) (IMO, 2001; Wickham, 2002). Additionally, because there is a nonlinear relationship between the volume of space and the amount of water mist needed to extinguish a given fire and because this relationship (referred to as the "mechanism of extinguishment") is not well understood, applications of water mist systems have been limited to those where fire test protocols have been developed, based on empirically tested system performance. Other market barriers for this option include additional space requirements for system storage compared with conventional HFC-227ea systems. Water mist systems can provide equivalent fire protection and life safety/health protection for Class B fuel hazards, where low temperature freezing is not a concern (USEPA, 2004).

This technology option is assumed to be applicable in large (≥3,000 m^3), new Class B total flooding application end uses, replacing HFCs (primarily HFC-227ea). This analysis assumes that systems designed to protect against Class B fire hazards represent an estimated 5% of the total flooding sector;[8] the additional adoption of water mist systems is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are estimated at $13.14 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs in developed countries are estimated at $0.36/cubic meter of protected space for additional electricity needed to heat/cool the additional space; these electricity costs are assumed to be 81% greater in developing countries. Annual costs are partly offset by annual savings associated with lower agent replacement costs, estimated at $0.28/cubic meter of protected space.

IV.6.4 Engineering Cost Data Summary

Table 6-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

IV.6.5 Marginal Abatement Cost Analysis

This section describes the methodological approach to the international assessment of abatement measures for fire extinguishing.

IV.6.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities in the developing and developed world. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

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[8] See footnote 3.

Table 6-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility Type	Project Lifetime (years)	Capital Cost (2010 USD)		Annual Revenue (2010 USD)	Annual O&M Costs, (2010 USD)		Abatement Amount (tCO_2e)
			Developed	Developing		Developed	Developing	
FK-5-1-12	New Class A total flooding	20	$9.49	$10.44	—	$0.03	$0.03	0.04
Inert gas	New Class A total flooding	20	$11.16	$12.28	$0.28	$0.17	$0.31	0.04
Water mist	Large, New Class B total flooding	20	$13.14	$14.45	$0.28	$0.36	$0.65	0.04

IV.6.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/class/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by Class (A or B), in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time; the market penetration used in this calculation is a modeled value that represents the assumed rate of penetration of the abatement option into fire protection systems over time, market willingness to adopt the option, and the turnover rate of existing fire protection systems. Table 6-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

Table 6-4: Technical Effectiveness Summary

Facility Abatement Option	Technical Applicability	Market Penetration Rate (2030)[a]	Reduction Efficiency	Technical Effectiveness (2030)[b]
FK-5-1-12—Developed	New Class A total flooding	40%	100%	**31%**
FK-5-1-12—Developing	New Class A total flooding	40%	100%	**12%**
Inert gas systems—Developed	New Class A total flooding	30%	100%	**20%**
Inert gas systems—Developing	New Class A total flooding	20%	100%	**6%**
Water mist systems—Developed	New Class B total flooding	75%	100%	**3%**
Water mist systems—Developing	New Class B total flooding	50%	100%	**1%**

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in Appendix H to this chapter.

[b] Technical effectiveness figures represent the percentage of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts associated with increased electricity consumption for heating/cooling of additional space, which is accounted for in the cost analysis.

IV.6.5.3 Estimating Abatement Project Costs and Benefits

Table 6-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for developed and developing countries. All options have positive break-even costs, because the costs of building and maintaining additional space are not offset by any available savings associated with lower agent replacement costs.

Table 6-5: Example Break-Even Prices for Abatement Measures in Fire Protection

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price[a] ($\$/tCO_2e$)
Developed					
FK-5-1-12	0.04	50.6	0.8	8.6	42.8
Inert gas systems	0.04	59.6	-2.8	10.1	46.6
Water mist systems	0.04	70.4	2.2	12.0	60.6
Developing					
FK-5-1-12	0.04	55.7	0.8	9.5	47.1
Inert gas systems	0.04	65.5	1.0	11.2	55.4
Water Mist Systems	0.04	77.4	10.2	13.2	74.4

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

The break-even prices presented in Table 6-5 represent model facilities for developed and developing countries. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section IV.6.5.4.

IV.6.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 0.7 and 6.4 $MtCO_2e$, respectively. There are no reductions in projected baseline emissions resulting from implementing currently available technologies that are cost-effective at projected prices. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to users or installers of fire extinguishing systems, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 6-6 and Figure 6-4 by major country and regional grouping at select break-even prices in 2030.

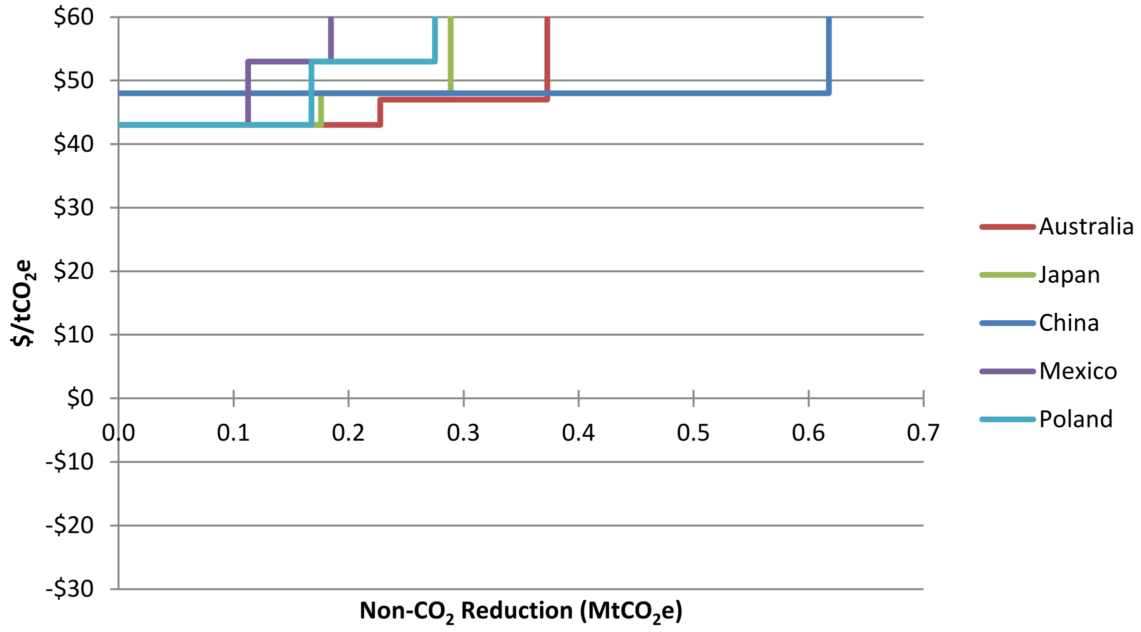
IV.6.6 Uncertainties and Limitations

One area of uncertainty is how capital costs for these mitigation technologies may vary internationally; cost estimates were developed for several countries when possible. In addition, it should be noted that the global implementation of each option is based on information currently available and expert opinion. Great uncertainty is associated with future projections of market behavior.

Table 6-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break-Even Price ($\$/tCO_2e$)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Australia	—	—	—	—	—	—	—	—	0.4	0.4	0.4
China	—	—	—	—	—	—	—	—	0.6	1.0	1.0
Japan	—	—	—	—	—	—	—	—	0.3	0.3	0.3
Mexico	—	—	—	—	—	—	—	—	0.1	0.2	0.2
Poland	—	—	—	—	—	—	—	—	0.2	0.3	0.3
Rest of Region											
Africa	—	—	—	—	—	—	—	—	0.4	0.6	0.6
Central and South America	—	—	—	—	—	—	—	—	0.5	0.7	0.7
Middle East	—	—	—	—	—	—	—	—	0.4	0.7	0.7
Europe	—	—	—	—	—	—	—	—	0.8	0.9	0.9
Eurasia	—	—	—	—	—	—	—	—	0.5	0.7	0.7
Asia	—	—	—	—	—	—	—	—	0.3	0.5	0.5
North America	—	—	—	—	—	—	—	—	0.1	0.1	0.1
Total	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**4.6**	**6.4**	**6.4**

Figure 6-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



References

ICF International. 2009. *Opportunities for Combined Heat and Power in Data Center*. Prepared for Oak Ridge National Laboratory. March 2009. Available at: https://www1.eere.energy.gov/manufacturing/datacenters/pdfs/chp_data_centers.pdf.

International Maritime Organization (IMO). November 30, 2001. *Performance Testing and Approval Standards for Fire Safety Systems: Fire Test Protocols for Fire-Extinguishing Systems*. Submitted by Germany to the International Maritime Organization Subcommittee on Fire-Protection, 46th session, Agenda item 12.

Kidde Fire Protection. 2011. *Fire Suppression System Engineered for Use with 3M™ Novec™ 1230 Fire Protection Fluid*. Ref. 6351-5-05/11. Available at: http://www.kfp.co.uk/utcfs/ws-438/Assets/6351-5_Novec_System.pdf.

Kucnerowicz-Polak, B. March 28, 2002. “Halon Sector Update.” Presented at the 19th Meeting of the Ozone Operations Resource Group (OORG), The World Bank, Washington, DC.

R.S. Means Company, Inc. 2007. *Means Square Foot Costs, 29th Annual Edition 2008*. Kingston, MA: R.S. Means Company, Inc. U.S. Energy Information Administration (EIA). 2008. “Average Retail Prices of Electricity, 1960-2007.” Available at: http://www.eia.doe.gov/emeu/aer/txt/ptb0810.html.

United Nations Environment Programme (UNEP). 2001. *Standards and Codes of Practice to Eliminate Dependency on Halons: Handbook of Good Practices in the Halon Sector*. United Nations Publication ISBN 92-807-1988-1. UNEP Division of Technology, Industry and Economics (DTE) under the OzonAction Programme under the Multilateral Fund for the Implementation of the Montreal Protocol, in cooperation with The Fire Protection Research Foundation.

U.S. Department of Labor, Bureau of Labor Statistics. 2011. Consumer Price Index. Obtained May 2011 at http://www.bls.gov/cpi/.

U.S. Energy Information Administration (EIA). October 19, 2011. “Average Retail Prices of Electricity, 1960-2010.” Annual Energy Review. Obtained December 2011 at: http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0810.

U.S. Environmental Protection Agency (USEPA). 2004. Analysis of Costs to Abate International Ozone-Depleting Substance Substitute Emissions. EPA 40-R-04-006. Washington, DC: U.S. Environmental Protection Agency. Available at: http://www.epa.gov/ozone/snap/emissions/downloads/ODSsubstituteemissions.pdf.

U.S. Environmental Protection Agency (USEPA). June 2006. *Global Mitigation of Non-CO_2 Greenhouse Gases.* EPA #430-R-06-005. Washington, DC: Office of Atmospheric Programs, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). October 2009. Marginal Abatement Cost Curve Analysis for Reduction of HFCs in Traditional Ozone Depleting Substance (ODS) End-Use Applications: Draft Report. Prepared by ICF International for U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

Werner, K. 2011. Personal communication between Kurt Werner of 3M and Pamela Mathis of ICF International, October 14, 2011.

Wickham, R. 2002. *Status of Industry Efforts to Replace Halon Fire Extinguishing Agents*. Wickham Associates. Stratham, New Hampshire. Available at: http://www.epa.gov/ozone/snap/fire/status.pdf.

Wickham, R. 2003. *Review of the Use of Carbon Dioxide Total Flooding Fire Extinguishing Systems*. Wickham Associates. Stratham, New Hampshire. Available at: http://www.epa.gov/ozone/snap/fire/co2/co2report2.pdf.

IV.7. PFC Emissions from Primary Aluminum Production

IV.7.1 Sector Summary

Emissions of the perfluorocarbons (PFCs)—perfluoromethane (CF_4) and perfluoroethane (C_2F_6)—are generated during brief process upset conditions in the aluminum smelting process. During the aluminum smelting process, when the alumina (Al_2O_3) in the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur. These voltage excursions are termed "anode effects" (AEs). AEs produce CF_4 and C_2F_6 emissions when carbon from the anode, instead of reacting with alumina, as it does during normal operating conditions, combines with fluorine from the dissociated molten cryolite bath. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these AEs; the more frequent and long-lasting the AEs, the greater the emissions.[1]

Global emissions of PFCs from primary aluminum production declined from 2000 to 2010, which is likely due to a variety of factors including improvement in process performance of existing smelter capacity, closure of high emitting facilities, and addition of low emitting new smelting capacity. However, global emissions of PFCs from this sector are expected to increase from an estimated value of 26 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010 to a projected value of 37 $MtCO_2e$ in 2030 (USEPA, 2012) (see Figure 2-1).[2] This projected increase is largely the result of an anticipated increase in demand for primary aluminum globally over the same period that is increasing at a higher rate than the assumed decrease in PFC emissions intensities (see Emissions from Aluminum Production below).

Five different electrolytic cell types are used to produce aluminum: Vertical Stud Soderberg (VSS), Horizontal Stud Soderberg (HSS), Side-Worked Prebake (SWPB), Center-Worked Prebake (CWPB), and Point Feed Prebake (PFPB).[3] PFPB is considered the most technologically advanced process to produce aluminum and all new greenfield smelters built in the world today utilize this technology. Existing, older and higher PFC emitting PFPB systems can further improve their anode effect performance by implementing management and work practices, as well as improved control software. Facilities using VSS, HSS, SWPB, and CWPB cells can reduce emissions by retrofitting smelters with emission-reducing technologies such as computer control systems and point-feeding systems, by shifting production to PFPB technology, and by adopting management and work practices aimed at reducing PFC emissions.

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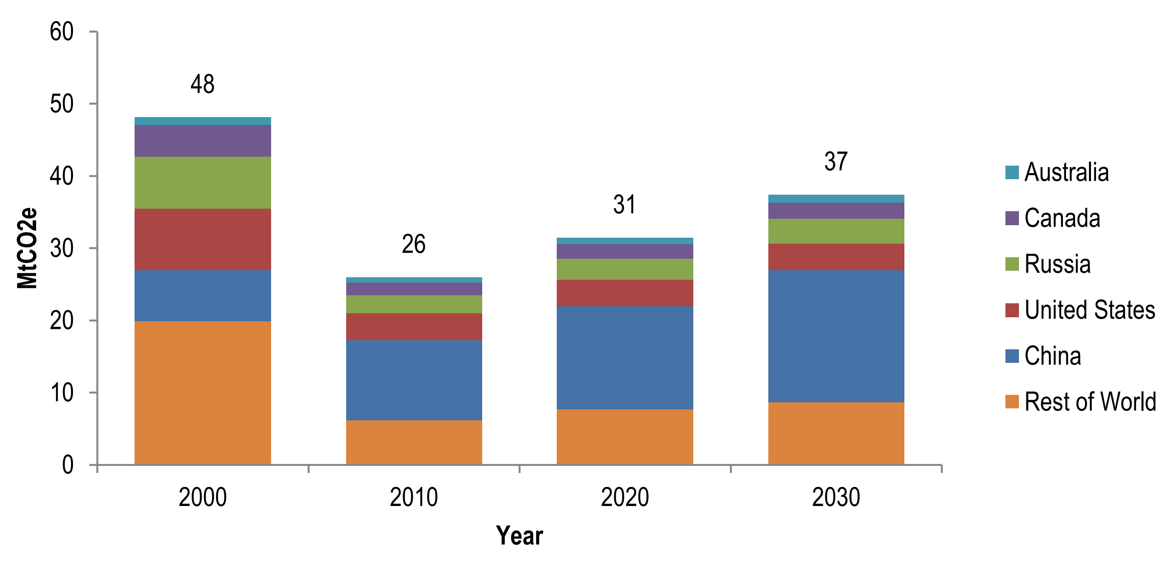
[1] It should be noted that over the last several years there has been the discovery and documentation of non-anode effect (NAE) related emissions. USEPA has supported some of the most significant work on NAE emissions. These emissions can be a significant, perhaps the major, source of PFC emissions in some smelter cells. It should also be noted that NAE emissions and NAE abatement measures are not addressed in this report.

[2] Please note that IAI (2011) publishes a historical value of 24.4 million metric tons of carbon dioxide equivalent ($MtCO_2e$) for 2010.

[3] It should be noted that PFPB and CWPB are essentially same cell design, but with different alumina feed processes.

However, in practice, the greatest potential for reduction in PFC emissions is through addition of new greenfield PFPB capacity in concert with the shutdown of existing high emitting facilities.[4]

Figure 7-1: PFC Emissions from Primary Aluminum Production: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012

Global abatement potential in the primary aluminum sector is 22 $MtCO_2e$ in 2030, which represents approximately 58% of the projected baseline emissions. Figure 7-2 shows the global marginal abatement cost (MAC) curves for 2010, 2020, and 2030.

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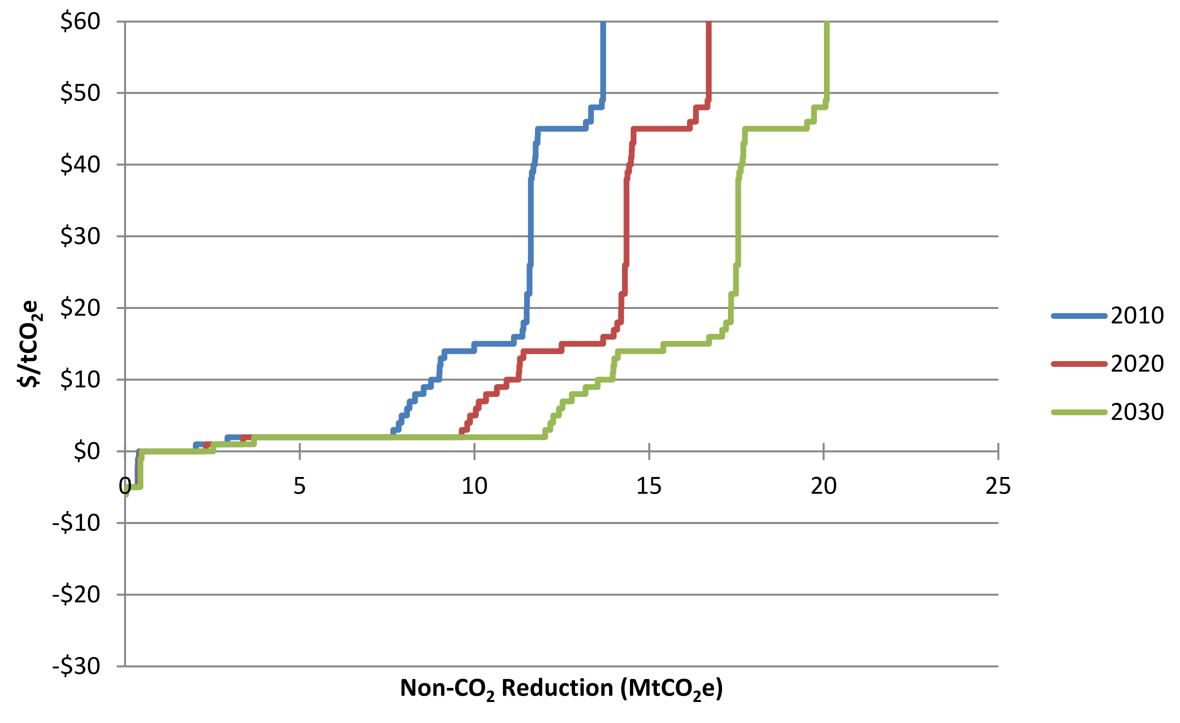
[4] More information on how global primary aluminum production according to cell type changed from 1990–2012 is available in "Figure 2: Primary aluminium smelting technology mix, 1990–2012" in *Results of the 2012 Anode Effect Survey: Report on the Aluminium Industry's Global Perfluorocarbon Gases Emissions Reduction Programme*, International Aluminium Institute, London, United Kingdom. Available online at: http://www.world-aluminium.org/media/filer_public/2013/08/20/2012_anode_effect_survey_report.pdf.

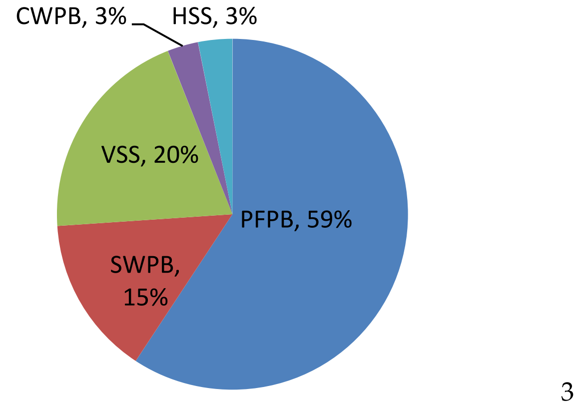
Figure 7-2: Global Abatement Potential in Primary Aluminum Production: 2010, 2020, and 2030



IV.7.2 Emissions from Primary Aluminum Production

Emissions of the PFCs CF_4 and C_2F_6 from primary aluminum production are estimated using a variety of activity data (e.g., historical emissions, aluminum production, nameplate capacity), key growth assumptions (e.g., production growth rate, country-specific trends), and emission factors. Calculations of PFC emissions from this sector are based on historical and expected levels of aluminum production and reported (i.e., International Aluminium Institute [IAI]) emission factors from historical experience. Emissions factors vary by aluminum production technology (e.g., electrolytic cell type) and region (e.g., China, rest of the world). More information on the estimation methodology is available in the update to the Global Emission Report (USEPA, 2012). Figure 7-3 shows the percentage of total PFC emissions according to production technology type in 2020.

Figure 7-3: Global PFC Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



For the purpose of developing the cost analysis, five different types of aluminum manufacturing facilities were considered, based on the technology types—VSS, HSS, SWPB, CWPB, and PFPB. Each model production facility analyzed produces 200,000 metric tons of aluminum annually.[5]

IV.7.2.1 Activity Data and Important Trends

The main activity data used to estimate emissions from primary aluminum production are historical and projected, country-specific, annual, primary aluminum production estimates.

Historical, country-specific, primary aluminum production data for 2010 are compiled from data provide by the U.S. Geological Survey (USGS) in *Mineral Yearbook: Aluminum* (USGS, 2011a). In 2010, world primary aluminum production totaled approximately 40,800 thousand metric tons (USGS, 2011a).[6]

Projected, country-specific, primary aluminum production data for 2015, 2020, 2025, and 2030 are estimated based on a combination of either applying the global aluminum production compounded annual growth rate of 2.5% per year as reported by the Intergovernmental Panel on Climate Change (IPCC) (Martchek, 2006) to the 2010 country-specific production estimate, or for certain countries, specific

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[5] It should be noted that the nameplate capacities of newly-built PFPB facilities around the world are typically larger than 200,000 metric tons.

[6] It should be noted that the world primary aluminum production total for 2010 was revised from the value available at the time of the analysis for this report—40,800 thousand metric tons—to 41,200 thousand metric tons in 2011 Mineral Yearbook: Aluminum [Advance Release]. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2011-alumi.pdf. Most of this increase was in India and Norway.

production projections provided in comments from the USGS (USGS, 2011b).[7] For countries with newly developed primary aluminum production (e.g., Qatar, Saudi Arabia) or newly re-commissioned primary production (e.g., Nigeria), the production projections are based on expected production capacity in future years. The country-specific aluminum production data described above is then disaggregated to cell technology type using primary aluminum smelting technology mix information derived from IAI's *2010 Anode Effects Survey Report* (IAI, 2011). For countries where future production is anticipated to be greater than the nameplate capacity in 2010, the excess production is assigned to PFPB technology. All current and future production in China is also assumed to be PFPB technology.

New primary aluminum production is increasingly taking place in emerging and developing regions, including China and the Middle East, and other countries, including Iceland, where there is the availability of long term, economically attractive power. New facilities open using new, less emissive PFPB technologies. In addition, over time older facilities, which use older, more emissive technologies, are likely to close, especially if they do not have continued access to competitive power (and labor) agreements. For example, China is anticipated to continue to be the major primary aluminum producer, and now uses PFPB technology across all of its facilities.[8] Other high-production countries use a mix of technology types, and production in some of these countries is anticipated to grow, while production in others is expected to remain constant. For example, after 2015, the United States is anticipated to no longer be a top five producer of primary aluminum. Thus, emissions in countries with new production are likely to grow more slowly than emissions from countries with existing production given similar increases in the rate of primary aluminum produced.

IV.7.2.2 Emission Estimates and Related Assumptions

As previously mentioned, global emissions of PFCs from primary aluminum production are estimate as 26 $MtCO_2e$ in 2010, and are projected to grow to 37 $MtCO_2e$ in 2030. Emissions from aluminum production can generally be described in terms of historical emissions and projected emissions. Historical, global, PFC emissions data for 1990 through 2010 are compiled from data provided by the IAI in *2010 Anode Effects Survey Report* (IAI, 2011). Projected, country-specific, PFC emissions data for 2010 through 2030 are estimated based on the product of the country-specific production by cell technology type and the technology-specific mean emission factor for the respective year.

Table 7-1 shows the top countries and regional breakout of emissions of PFCs from primary aluminum production from 2010 to 2030.

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[7] It should be noted that growth rates in primary aluminum production have exceeded this value over the past decade—e.g., 5.3% this decade based on IAI statistics (see http://www.world-aluminium.org/statistics/primary-aluminium-production/#data)—and aluminum industry leaders have publically estimated growth rates of at least 5% in the foreseeable future. Growth rates in aluminum production have historically tracked GDP growth in developed countries, and aluminum growth rates have been historically greater than GDP growth in developing countries based on the need for aluminum in infrastructure and transportation development. In addition, production growth rates are region specific, and consumption is not driven by an average (mean) global GDP growth. Rather, aluminum demand is driven by fast growing economies, thus is more influenced by high growth GDP regions. Therefore, the published value of 2.5% available at the time of the analysis for this report is likely too small, even taking into account the current global slowdown. Out to 2020 and beyond, as China, India and other countries increasingly urbanize, this growth rate will likely further accelerate.

[8] It should be noted that while China has converted to PFPB technology, the country's cell designs and control strategies result in PFC emission factors great than those for PFPB technology operated in the rest of world (ROW). As a result, separate PFPB emission factors were applied for China versus ROW.

Table 7-1: Projected Baseline Emissions from Primary Aluminum Production: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
Top 5 Emitting Countries						
China	11.1	12.6	14.3	16.2	18.3	2.5%
United States	3.7	3.7	3.6	3.6	3.6	−0.1%
Russia	2.5	2.8	3.0	3.2	3.4	1.6%
Canada	1.7	1.8	2.0	2.1	2.3	1.5%
Australia	0.8	0.8	0.9	1.0	1.1	1.5%
Rest of Regions						
Africa	1.2	1.2	1.3	1.4	1.4	1.1%
Central & South America	0.8	0.8	0.9	1.0	1.1	1.8%
Middle East	1.2	1.8	1.9	2.0	2.0	2.6%
Europe	1.8	1.9	2.1	2.3	2.4	1.5%
Eurasia	0.3	0.3	0.4	0.4	0.4	1.8%
Asia	0.9	1.0	1.1	1.2	1.3	1.6%
North America	—	—	—	—	—	—
World Total	**26.0**	**28.9**	**31.4**	**34.3**	**37.4**	**1.8%**

[a] CAGR = Compound Annual Growth Rate
Source: USEPA, 2012

IV.7.3 Abatement Measures and Engineering Cost Analysis

PFC emission reductions can primarily be achieved by installing/upgrading process computer control systems[9] and installing alumina point-feed systems.[10] The two abatement options considered for this analysis are (1) a minor retrofit involving the upgrade of process computer control systems only and (2) a major retrofit involving both the installation/upgrade of process computer control systems and the installation of alumina point-feed systems.[11] The installation of alumina point-feed systems is not analyzed on its own, because it would be very unlikely that an aluminum production facility would install alumina point-feed systems without also installing or upgrading process computer control systems.[12]

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[9] Process computer control systems control the repositioning of carbon anodes as they are consumed and provide greater control over raw material (alumina) feeding. All smelters operate with process control computers. The upgrade would involve changes in the algorithms controlling feed and anode effect detection.

[10] Point-feed systems allow more precise alumina feeding.

[11] A major retrofit results in PFPB technology, which is the state-of-the-art technology in aluminum production. Conversion to PFPB technology results in the most reliable increases in operational and production efficiency; although the capital outlay for this option is significant. In addition, retrofit options are usually implemented after extensive computer modeling and large-scale development work is conducted on test cells.

[12] It should be noted that, as previously mentioned, existing, older, and higher PFC emitting systems can further improve their anode effect performance by implementing management and work practices, as well as improved control software.

IV.7.3.1 Minor Retrofit

A minor retrofit involves the installation/upgrade of process computer control systems. Minor retrofits can be performed at any facility type other than the state-of-the-art PFPB facilities. For the purpose of the cost analysis, a minor retrofit has a lifetime of 10 years for VSS, HSS, and SWPB facility types; 20 years at the CWPB facility; and 30 years at the PFPB facilities, based on expert judgment. The lifetime of the minor retrofit at older facilities is shorter because the estimated remaining lifetime of the facilities themselves is shorter.

- **Capital Costs:** Capital costs represent the costs associated with purchasing and installing the process computer control systems at the aluminum production facilities. The capital costs, obtained from International Energy Agency (IEA) (2000) and confirmed by Marks (2011a), range from $6 million to $8 million (2010 USD), depending on the facility type.
- **Annual O&M Costs:** The annual O&M costs associated with the retrofits are strictly the additional operating costs for the increased aluminum production. The additional operating costs were assumed to equal the percentage increase in current efficiency multiplied by the capital costs of the retrofit, which is the method used to estimate O&M costs by IEA (2000). These costs range from approximately $60,000 to $120,000 (2010 USD), depending on the facility type.
- **Annual Revenue:** Based on expert judgment, it is assumed that the increased current efficiency (aluminum production/unit of electricity) resulting from the retrofits would be used by the model facilities to produce more aluminum with the same amount of electricity consumption as before (rather than producing the previous levels of aluminum production and realizing the electricity savings).[13] Consequently, additional revenues of approximately $0.5 million to $1 million (2010 USD) are associated with the minor retrofit option, depending on the facility type.
- **Technical Lifetime**: The expected lifetime range is assumed to be 10 years for VSS, HSS, and SWPB facility types. Longer lifetimes of 20 and 30 years are applied to CWPB and PFPB facility types, respectively.
- **Reduction Efficiency**: The minor retrofits reduction efficiency varies by facility type (see Table 7-2).

Table 7-2: Primary Aluminum Production Abatement Options

Abatement Option	Reduction Efficiency	Applicability
Minor retrofit	24%–55%	All facility types other than state-of-the-art PFPB facilities
Major retrofit	77%–96%	VSS, HSS, SWPB facilities

IV.7.3.2 Major Retrofit

A major retrofit involves both the installation/upgrade of process computer control systems and the installation of alumina point-feed systems. A major retrofit results in AE performance approaching that of PFPB technology, which is the state-of-the-art technology in aluminum production. A major retrofit also results in increases in operational and production efficiency, although the capital outlay for this option is significant. In addition, retrofit options are usually implemented after extensive computer modeling and large-scale development work are conducted on test cells. Major retrofits can be performed

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[13] Note that this is a simplifying assumption for the purpose of this analysis; any increase in production would be driven by demand for aluminum, not specifically driven by a set level of electricity consumption.

for the older facility types (VSS, HSS, and SWPB). According to Marks (2011b), there is no opportunity for conventional CWPBs to install point feeders because they already have “bar break” feed systems, which have roughly the same anode effect performance as point feeders; and by definition, a PFPB model facility has point-feeding systems, so there is no opportunity for additional application.

For the purpose of the cost analysis, a major retrofit has a lifetime of 10 years, based on expert judgment.

- **Capital Costs:** Capital costs represent the costs associated with purchasing and installing the process computer control systems and alumina point-feeding technologies at the aluminum production facilities. The capital costs, obtained from IEA (2000) and confirmed by Marks (2011a), range from $12 million to $90 million (2010 USD), depending on facility type.
- **Annual Operation and Maintenance (O&M) Costs:** The annual O&M costs associated with the retrofits are strictly the additional operating costs for the increased aluminum production. The additional operating costs were assumed to equal the percentage increase in current efficiency multiplied by the capital costs of the retrofit, which is the method used to estimate O&M costs by IEA (2000), and range from $350,000 to $3.4 million (2010 USD), depending on facility type.
- **Annual Revenue:** Based on expert judgment, it is assumed that the increased current efficiency (aluminum production/unit of electricity) resulting from the retrofits would be used by the model facilities to produce more aluminum with the same amount of electricity consumption as before (rather than producing the previous levels of aluminum production and realizing the electricity savings). Increased current efficiencies for each facility and retrofit are available from IEA (2000). For a major retrofit, these revenues range from $1 million to $2 million (2010 USD), depending on facility type.
- **Technical Lifetime:** The expected lifetime of this technology is 10 years.
- **Reduction Efficiency:** This analysis assumes a reduction efficiency of 78% for HSS, 96% for SWPB, and 77% for VSS facilities.

IV.7.3.3 Engineering Cost Data Summary

Table 7-3 presents the engineering cost data for each abatement measure outlined above, including all cost parameters necessary to calculate the break-even price.

IV.7.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the primary aluminum production sector.

Table 7-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility Type	Project Lifetime (Years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
Minor retrofit	VSS	10	$5,980,801	$1,019,402	$119,616	21,277
	HSS	10	$5,980,801	$509,701	$59,808	112,894
	SWPB	10	$6,238,348	$764,552	$93,575	41,900
	CWPB	20	$7,125,452	$509,701	$71,255	83,800
	PFPB	30	$8,026,865	$509,701	$80,269	129,607
Major retrofit	VSS	10	$84,546,778	$2,038,805	$3,381,871	112,894
	HSS	10	$89,039,533	$1,019,402	$1,780,791	41,900
	SWPB	10	$11,804,213	$1,529,104	$354,126	83,800

IV.7.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous Section 7.3 of this chapter at the five model facilities to calculate a break-even price for the applicable options at each facility.

IV.7.4.2 Definition of Model Facilities

As mentioned at the beginning of this chapter, five different electrolytic cell types are used to produce aluminum—VSS, HSS, SWPB, CWPB, and PFPB, which is considered the most technologically-advanced process to produce aluminum.

A facility's performance may be represented by the mean or median (depending on the size of the cohort of facilities and the range of performance) PFC emission factor—PFC emissions per unit production (e.g., metric tons CO_2e/metric ton Al)—for a particular cell technology type. However, in the case of PFPB technology, the universe of facilities using this technology is further subdivided into state-of-the-art (i.e., newer) PFPB facilities for which no abatement measures are applicable and other (i.e., older) PFPB facilities for which certain abatement measures are an option. The performance for state-of-the-art (as opposed to other) PFPB technology is therefore better represented by a PFC emission factor less than the average (i.e., the median). Table 7-4 presents a description of the model facilities considered for this analysis.

IV.7.4.3 Assessment of Technical Effectiveness

To assess the abatement potential from each technology option, one additional parameter is needed, which is termed the technical effectiveness. The technical effectiveness parameter determines the share of emissions reductions attributed to each abatement measure. Similar to other industrial process sectors covered in this report, the technical effectiveness parameter is defined as the percentage of emissions reductions achievable by each technology/facility combination. Estimating this parameter requires assumptions regarding the distribution of emissions by manufacturing process (i.e., VSS, HSS, SWPB, CWPB, and PFPB) in addition to process-specific estimates of technical applicability and market penetration. The technical applicability, market penetration, and reduction efficiency assumptions are held constant for all model years. Table 7-5 reports the technical applicability parameters estimated of each abatement measure/facility type combination. Table 7-5 also presents the market penetration,

Table 7-4: Description of Primary Aluminum Production Facilities

Facility Type	Description
VSS	This facility uses VSS technology, with an average PFC emission factor of 1.01 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.
HSS	This facility uses HSS technology, with an average PFC emission factor of 1.07 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.
SWPB	This facility uses SWPB technology, with an average PFC emission factor of 5.41 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.
CWPB	This facility uses CWPB technology, with an average PFC emission factor of 0.51 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.
PFPB (state of the art)	This facility uses state-of-the-art PFPB technology, with a median PFC emission factor of 0.23 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.
PFPB (other)	This facility uses other PFPB technology, with an average PFC emission factor of 0.51 metric tons CO_2e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.[a]

[a] It should be noted that "state of the art" has been improving rapidly with respect to anode effect performance and the best PFPB facilities (top 10%) are performing at better than 0.06 metric tons CO_2e/metric ton Al. Median performance for all IAI non-Chinese producers is about 0.23 metric tons CO_2e/metric ton Al, while median Chinese PFPB performance is about 0.7 metric tons CO_2e/metric ton Al.

Table 7-5: Technical Effectiveness Summary

Abatement Option	Model Facility Type	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Minor retrofit					
	VSS	27%	100%	39%	**11%**
	HSS	100%	50%	39%	**20%**
	SWPB	100%	50%	24%	**12%**
	CWPB	100%	100%	55%	**55%**
	PFPB	100%	100%	55%	**55%**
Major retrofit					
	VSS	73%	100%	77%	**56%**
	HSS	100%	50%	78%	**39%**
	SWPB	100%	50%	96%	**48%**

technical applicability, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameter. Technical effectiveness is equal to the product of the technical applicability, market penetration, and reduction efficiency.

Technical applicability factor for VSS is based on the assumption that roughly 27% of VSS capacity already has point feeding (Marks, 2011b). This percentage is described in more detail in Appendix I.

IV.7.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.7.3 to calculate the break-even price for each mitigation option/facility combination. Table 7-6 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

Table 7-6: Example Break-Even Prices for Abatement Measures in Primary Aluminum Production

Abatement Option	Model Facility Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Minor retrofit						
	VSS	21,277	$76	−$42	$19	**$4**
	HSS	41,900	$39	−$11	$10	**$9**
	SWPB	129,607	$13	−$5	$3	**$2**
	CWPB	56,667	$25	−$8	$4	**$13**
	PFPB	56,087	$25	−$8	$3	**$14**
Major retrofit						
	VSS	112,894	$203	$12	$50	**$120**
	HSS	83,800	$288	$9	$71	**$113**
	SWPB	518,429	$6	−$2	$2	**$1**

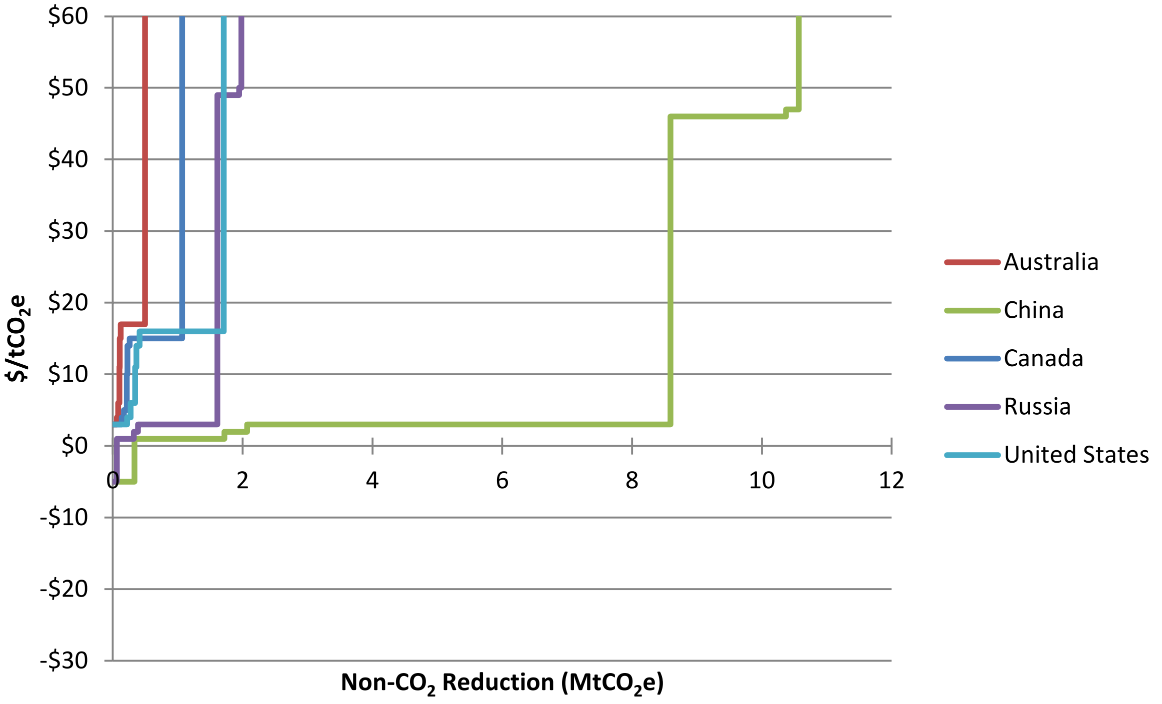
IV.7.4.5 MAC Analysis Results

The global abatement potential for PFC emissions in the primary aluminum production sector is 22 $MtCO_2e$, which is approximately 58% of total projected emissions in 2030. Table 7-7 presents the cumulative reductions achieved at selected break-even prices. Figure 7-4 shows the MAC curve for the top five emitting countries and the rest of world.

Table 7-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($\$/tCO_2e$)										
Country/Region	**10**	**5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Australia	—	—	—	0.1	0.1	0.1	0.5	0.5	0.5	0.5	0.6
Canada	—	—	—	0.21	0.2	1.1	1.1	1.1	1.1	1.1	1.3
China	—	0.3	1.7	8.6	8.6	8.6	8.6	8.6	10.6	10.6	10.6
Russia	—	0.1	0.3	1.6	1.6	1.6	1.6	1.6	2.0	2.0	2.0
United States	—	—	—	0.34	0.4	1.7	1.7	1.7	1.7	1.7	2.1
Rest of Region											
Africa	—	0.0	0.3	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Central and South America	—	—	0.0	0.2	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Middle East	—	—	0.0	0.2	0.4	0.8	0.9	0.9	0.9	1.0	1.2
Europe	—	—	0.0	0.2	0.6	0.8	0.9	1.1	1.1	1.3	1.4
Eurasia	—	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Asia	—	—	0.0	0.1	0.6	0.6	0.6	0.6	0.6	0.7	0.7
North America	—	—	—	—	—	—	—	—	—	—	—
World Total	**—**	**0.43**	**2.53**	**12.4**	**14.0**	**16.7**	**17.3**	**17.5**	**20.1**	**20.5**	**21.6**

Figure 7-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



IV.7.4 Uncertainties and Limitations

The emission projections (i.e., baseline emissions) account for the historical reduction in the effective emission factor (i.e., metric ton CO_2e/metric ton Al) realized by facilities, but do not assume that aluminum producers have conducted retrofits, or will continue to introduce technologies and practices aimed at reducing PFC emissions. That said, the global primary aluminum industry through the IAI has a voluntary PFC emission reduction goal of reduce emissions of PFCs per metric ton of aluminum by at least 50% by 2020 as compared to 2006 (IAI, 2013). In addition, commissioning of new—less emissive—facilities to meet global demand will also have the result of reducing the effective emission factor.

References

Harbor Intelligence. 2009. "Interesting Trends in the Chinese Aluminum Market." Obtained at: http://www.harboraluminum.com/archivos/China_Aluminum_Monitor_(Jan_2009).pdf.

International Aluminium Institute (IAI). 2010. *Results of the 2009 Anode Effects Survey: Report on the Aluminum industry's Global Perfluorocarbon Gases Emissions Reduction Program*. London, United Kingdom. July 5. Obtained at: http://www.world-aluminium.org/cache/fl0000361.pdf.

International Aluminium Institute (IAI), 2011. *Results of the 2010 Anode Effects Survey: Report on the Aluminum Industry's Global Perfluorocarbon Gases Emissions Reduction Program*. London, UK. August 24.

International Aluminium Institute (IAI), 2013. *Results of the 2012 Anode Effects Survey: Report on the Aluminum Industry's Global Perfluorocarbon Gases Emissions Reduction Program*. London, UK.

International Energy Agency (IEA). 2000. Greenhouse Gas Emissions from the Aluminium Industry. The IEA Greenhouse Gas R&D Program. Cheltenham, United Kingdom.

London Metals Exchange (LME). 2011. LME Official Prices for Aluminum. Obtained at: http://www.lme.com/aluminium.asp. Accessed on October 31, 2011.

Marks, J. 2006. Personal communication with Jerry Marks, IAI. as cited in USEPA. 2006. *Global Mitigation of Non-*CO_2 *Greenhouse Gases*. Washington, DC: U.S. Environmental Protection Agency.

Marks, J. 2011a. Personal communication with Jerry Marks via e-mail. June 22.

Marks, J. 2011b. Personal communication with Jerry Marks via e-mail. July 14.

Martchek, K.J. 2006. Modeling More Sustainable Aluminum: Case Study. *Int. J. LCA* 11(1) 2006:4. Obtained at: http://www.alcoa.com/sustainability/en/pdfs/KMartchek_IJLCA_7772.pdf.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Geological Survey (USGS). 2011a. *2010 Mineral Yearbook: Aluminum [Advanced Release]*. U.S. Geological Survey. Reston, VA. September. Available at http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/.

U.S. Geological Survey (USGS). 2011b. Personal communication with E. Lee Bray, U.S. Geological Survey Mineral Commodity Specialist.

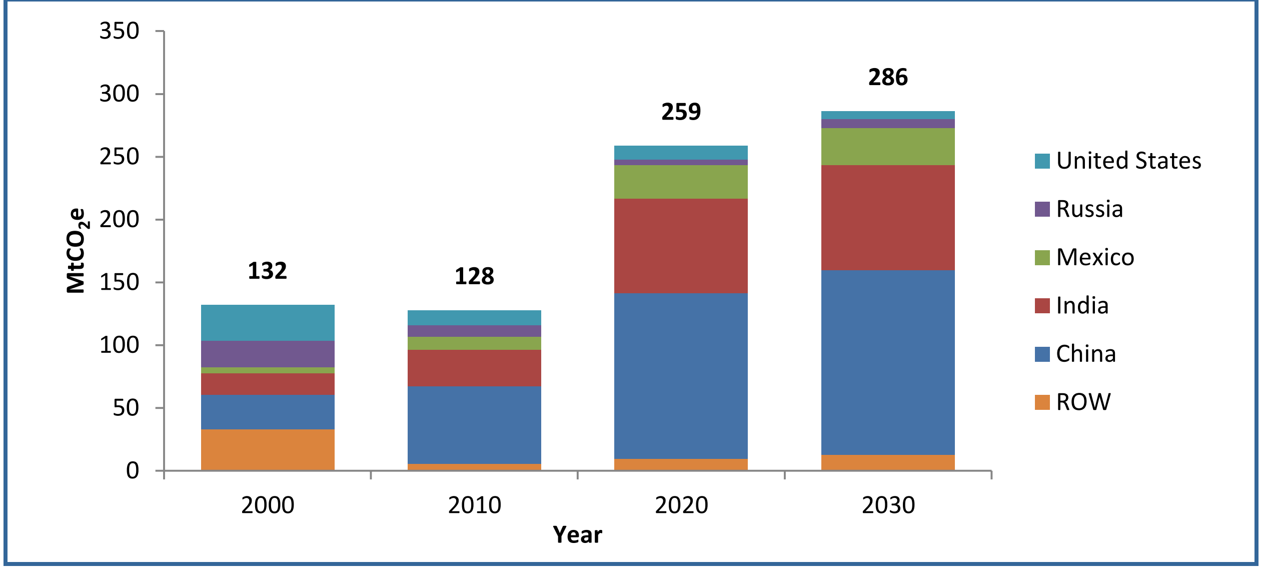
IV.8. HFC-23 Emissions from HCFC-22 Production

IV.8.1 Sector Summary

Trifluoromethane (HFC-23) is generated and emitted as a by-product during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used both in emissive applications (primarily air-conditioning and refrigeration) and as a feedstock for production of synthetic polymers. Because HCFC-22 depletes stratospheric ozone, its production for dispersive uses is scheduled to be phased out under the Montreal Protocol. However, feedstock production, a nondispersive use, is permitted to continue indefinitely.

Global HCF-23 emissions are projected to more than double, growing from 127.9 million metric tons of carbon dioxide equivalent (MtCO$_2$e) in 2010 to 286.4 MtCO$_2$e in 2030. Figure 8-1 shows the projected changes in annual emissions of HFC-23 out to year 2030. China, India, and Mexico are projected to see the largest increases in HFC-23 emissions primarily because of increased HCFC-22 production capacity in these countries.

Figure 8-1: HCF-23 Emissions from HCFC-22 Production: 2000–2030 (MtCO$_2$e)



Source: U.S. Environmental Protection Agency (USEPA), 2012

The production of HCFC-22 in developed countries has decreased in the last decade, while growth of annual HCFC-22 production in developing countries has grown substantially, driven primarily by the demand for its use as feedstock in fluoropolymer manufacture (Montzka et al., 2010). All HCFC-22 producers in developed countries have implemented either process optimization and/or thermal destruction to reduce HFC-23 emissions. In a few cases, HFC-23 is collected and used as a substitute for Ozone Depleting Substances (ODSs), mainly in very-low temperature refrigeration and air-conditioning systems.[1] Several HCFC-22 production facilities in developing countries participate in the United Nations

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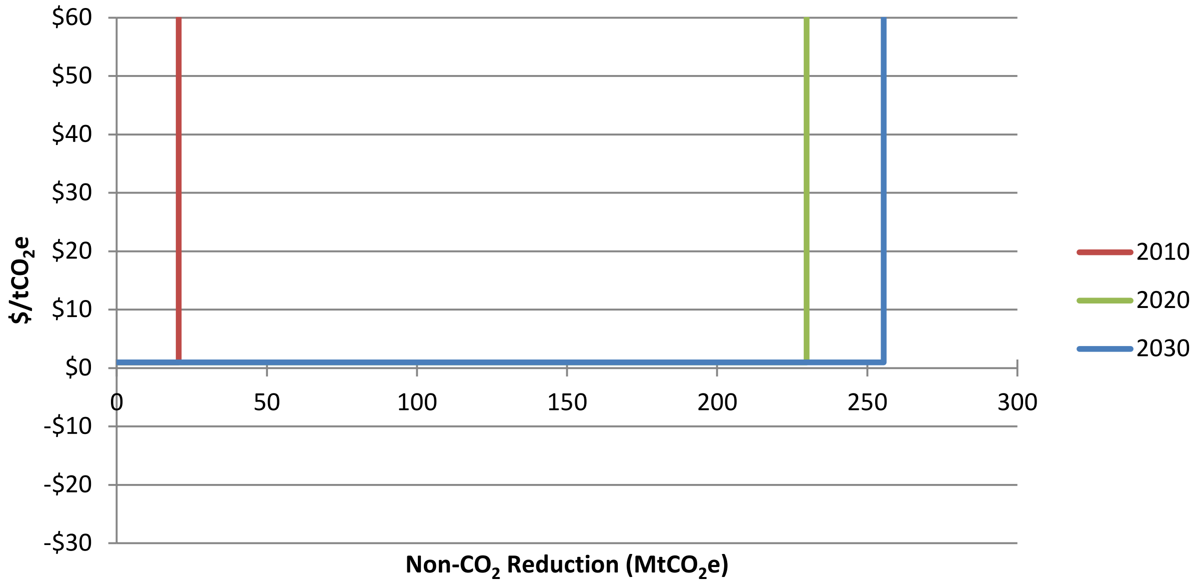
[1] Emissions from this use are quantified in the air conditioning and refrigeration chapters and are therefore not included here.

Framework on Climate Change's Clean Development Mechanism (CDM) and through their destruction of coproduced HFC-23, they are eligible for Certified Emission Reduction (CER) credits. Such projects were approved beginning in 2003, and although currently 19 projects are approved, a large fraction of facilities producing HCFC-22 in developing countries are not CDM participants, in part because not all HCFC-22 facilities are eligible to earn credits under CDM. Current CDM rules state that HCFC-22 production facilities must have an operating history of at least three years between January 2000 and December 2004 in order to be eligible for a project. A study published in 2010 reported that approximately 57 percent of HCFC-22 were produced but not covered by existing CDM projects (Montzka et al., 2010). In another assessment, approximately 43 production lines within 26 existing HCFC-22 facilities were identified in Article 5 countries. There are about 23 production lines within 17 facilities in Article 5 countries with CDM Projects approved or awaiting approval (Hufford et al., 2012).

This analysis examines the costs to mitigate HFC-23 emissions from HCFC-22 production plants that do not have incineration technology installed and the costs to mitigate HFC-23 emissions from those facilities that have thermal destruction devices installed because of a CDM project but are assumed not to choose to continue their operation after the CDM crediting period expires. There is uncertainty regarding the future of HFC-23 CDM projects and compliance carbon markets in general; the assumptions chosen to develop projected abatement potential in this analysis represent one potential scenario. A discussion regarding the limitations of this analysis is presented in Section IV.8.4

Global mitigation potential of HFC-23 from HCFC-22 production in 2030 is 255 $MtCO_2e$, roughly 89% of the projected baseline emissions. Figure 8-2 presents the sector marginal abatement cost (MAC) curves for 2010, 2020, and 2030. This analysis examines the abatement option employed by production facilities to destroy HFC-23—installation and/or operation of thermal oxidation devices; as shown in the figure, abatement can be achieved at a low break-even price between $\$0/tCO_2e$ and $\$1/tCO_2e$.

Figure 8-2: Global Abatement Potential in HCFC-22 Production: 2010, 2020, and 2030



IV.8.1.1 Emissions from HCFC-22 Production

In the production of HCFC-22, HFC-23 is separated as a vapor from the condensed HCFC-22, and emissions occur through venting of HFC-23 to the atmosphere as an unwanted by-product.

For the purpose of evaluating the cost of reducing HFC-23 emissions from HCFC-22 production, this analysis considers reduction costs for a typical HCFC-22 production facility, characterized as having a production capacity of approximately 22,400 metric tons of HCFC-22 (the average production capacity of all HCFC-22 production plants) and HCFC-22 production at 82% of that production capacity based on production estimates (Will et al., 2004; 2008).

Additionally, this analysis considers several possibilities for the level of abatement technology used at the typical HCFC-22 production facility, reflecting different levels of emissions. The analysis examines four possible categories of facilities. The first two categories address current and historical levels of emissions from current facilities:

1. *Facilities with abatement controls in place already.* This level of abatement is true for all production facilities in the Annex I countries and facilities that have CDM projects. Since the start of Clean Development Mechanism (CDM) projects for HCFC-22 production, there have been 19 CDM projects; the majority of these projects are at HCFC-22 production facilities in China (11 in total), followed by India (5), Argentina (1), Mexico (1), and the Republic of Korea (1).
2. *Facilities with no abatement technology controls installed.* Such facilities currently exist in China and Venezuela.

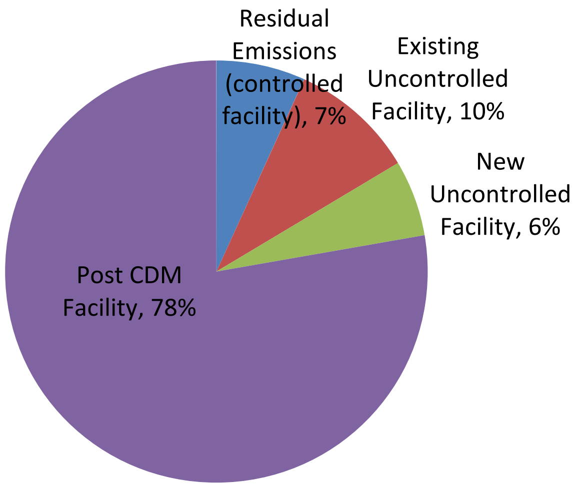
The third and fourth facility categories assist in projecting future emissions from current and new facilities:

1. *New facilities entering the market.* To meet future global demand of HCFC-22, the analysis estimates new facilities to enter the market once projected production for a non-Annex country exceeds current capacity of the facilities within the country. New facilities are characterized as being built without control technology.
2. *Facilities having previously participated in a CDM project, but not currently incinerating.* When a CDM crediting period is over and the CDM project is completed, this analysis assumes that the incineration device installed as a result of the CDM project will not be kept in operation. The cost assumptions for these facilities differ from those of a new uncontrolled facility in that no capital costs will be needed to install the incinerator. This analysis assumes that all facilities participating in CDM have completed their crediting periods by 2020.

IV.8.1.2 Activity Data or Important Sectoral or Regional Trends

The primary activity data for HFC-23 emissions from this sector are the level of HCFC-22 production in the country and whether the production uses any HFC-23 abatement. A total of 20 countries produce HCFC-22, and of this total, only 12 countries are assumed to continue to produce HCFC-22 between 2015 and 2030. Regionally, abatement of HFC-23 emissions is occurring in developed countries, and in developing countries, abatement is driven by the CDM incentives for HFC-23 abatement. Thus, the most significant regional trends are driven by assumptions about the extent to which abatement is occurring by country and whether that abatement will continue in the future. Overall, global HCFC-22 production is assumed to continue to grow at a modest rate to meet the demand of HCFC-22 use for feedstock in fluoropolymer manufacturing, despite restrictions on HCFC-22 production for dispersive uses of HCFC-22 in response to the controls of HCFC-22 consumption under the Montreal Protocol. Figure 8-3 shows the projected distribution of global HFC-23 emissions by facility type in 2020.

Figure 8-3: Global HFC-23 Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



IV.8.1.3 Emission Estimates and Related Assumptions

Emissions of HFC-23 from HCFC-22 production were estimated to be 127.9 $MtCO_2e$ in 2010, growing to 286.4 $MtCO_2e$ in 2030. Table 8-1 presents the projected annual HFC-23 emissions between 2010 and 2030 for the top five emitting countries and rest of global regions.

Table 8-1: Projected Baseline Emissions from HCFC-22 Production: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010 2030)
Top 5 Emitting Countries						
China	62.1	70.0	132.2	142.3	147.0	4.4%
India	29.1	37.3	75.2	80.9	83.6	5.4%
Mexico	10.2	13.1	26.5	28.5	29.4	5.4%
Russia	9.3	6.9	4.6	5.9	7.5	-1.1%
United States	11.8	10.6	10.8	7.9	6.0	-3.3%
Rest of Region						
Africa	—	—	—	—	—	—
Central & South America	2.5	2.8	3.7	4.0	4.1	2.6%
Middle East	—	—	—	—	—	—
Europe	1.0	1.0	1.1	1.4	1.8	2.9%
Eurasia	—	—	—	—	—	—
Asia	1.9	2.4	4.7	5.4	6.8	6.7%
North America	—	—	—	—	—	—
World Total	**127.9**	**144.2**	**258.8**	**276.3**	**286.4**	**4.1%**

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

To estimate historical emissions of HFC-23, dispersive and feedstock HCFC-22 production levels were developed and subsequently multiplied by a HFC-23/HCFC-22 coproduction ratio (i.e., tons of HFC-23 emitted per ton of HCFC-22 produced). To account for thermal abatement technologies in the baseline, the analysis used a lower HFC-23/HCFC-22 production ratio. Depending on how well the process is optimized, these ratios can range from 1.4% to 4% (Rotherham, 2004; McCulloch and Lindley, 2007). The emission rate for Annex I countries was assumed to be 2% across the entire time series (Montzka et al., 2010). The emission rate for non-Annex I countries and Russia was assumed to be 3% from 1990 through 2005 (USEPA, 2006) and 2.9% from 2006 through 2007 (Miller et al., 2010). The lower emission rate takes into account any HFC-23 emission offsets from CDM projects in these countries and the Joint Implementation (JI) project at Russia's HCFC-22 plant in Perm. Where UNFCCC-reported HFC-23 emission estimates were available through the UNFCCC flexible query system, these estimates were used in place of estimates calculated using production data (UNFCCC, 2009).

HFC-23 emission projections were developed for Annex I countries including Germany, Japan, the Netherlands, Russia, Spain, and the United States. For the United States, National Communications projections of emissions were used for 2010 to 2020 (UNFCCC, 2009); emissions trends were used to project HFC-23 emissions for the remainder of the time series (2025 through 2030). For all other Annex I countries, the dispersive production and feedstock production portion of emissions were projected separately to account for the decline in the production for dispersive purposes because of the phaseout requirements of the Montreal Protocol. To project the feedstock production portion of HFC-23 emissions, USEPA applied the 5% global growth rate of feedstock HCFC-22 production as reported in Montzka et al. (2010).

HFC-23 emission projections were developed for non-Annex I countries including China, India, Mexico, South Korea, and Venezuela. To do so, non-Annex I aggregate HCFC-22 production was projected for both dispersive and feedstock production; the production was then disaggregated by country using the percentage of each country's contribution to 2007 non-Annex I HCFC-22 production. Each country's HCFC-22 projected production was then apportioned into four different model facilities for each developing country, and two HFC-23/HCFC-22 coproduction ratios were applied to develop emission estimates—to address the varying use of abatement technologies by facilities. Table 8-2 presents the assumed distribution of baseline emissions by model facility and country/country group over time.

Table 8-2: Distribution of HCF-23 Emissions by Location and Facility Type: 2010–2030

Country/Group	Model Facility Type	2010	2015	2020	2025	2030
Annex I	Residual emissions	100%	100%	100%	100%	**100%**
Annex I	Non-CDM and uncontrolled facility	0%	0%	0%	0%	**0%**
Annex I	New uncontrolled facility	0%	0%	0%	0%	**0%**
Annex I	Post-CDM facility	0%	0%	0%	0%	**0%**
Argentina	Residual emissions	100%	100%	0%	0%	**0%**
Argentina	Non-CDM and uncontrolled facility	0%	0%	0%	0%	**0%**
Argentina	New uncontrolled facility	0%	0%	0%	0%	**0%**
Argentina	Post-CDM facility	0%	0%	100%	100%	**100%**
China	Residual emissions	68%	68%	0%	0%	**0%**
China	Non-CDM and uncontrolled facility	32%	32%	17%	16%	**15.9%**
China	New uncontrolled facility	0%	0%	0%	6%	**8.8%**
China	**Post-CDM facility**	**0%**	**0%**	**83%**	**78%**	**75.2%**

(continued)

Table 8-2: Distribution of HCF-23 Emissions by Location and Facility Type: 2010–2030 (continued)

Country/Group	Model Facility Type	2010	2015	2020	2025	2030
India	Residual emissions	100%	78%	0%	0%	**0%**
India	Non-CDM and uncontrolled facility	0%	0%	0%	0%	**0%**
India	New uncontrolled facility	0%	22%	14%	20%	**22.6%**
India	Post-CDM facility	0%	0%	86%	80%	**77.4%**
Mexico	Residual emissions	100%	78%	0%	0%	**0%**
Mexico	Non-CDM and uncontrolled facility	0%	0%	0%	0%	**0%**
Mexico	New uncontrolled facility	0%	22%	14%	20%	**22.6%**
Mexico	Post-CDM facility	0%	0%	86%	80%	**77.4%**
South Korea	Residual emissions	0%	0%	0%	0%	**0%**
South Korea	Non-CDM and uncontrolled facility	0%	0%	0%	0%	**0%**
South Korea	New uncontrolled facility	0%	11%	14%	20%	**22.6%**
South Korea	Post-CDM facility	100%	89%	86%	80%	**77.4%**
Venezuela	Residual emissions	0%	0%	0%	0%	**0%**
Venezuela	Non-CDM and uncontrolled facility	100%	89%	86%	80%	**77.4%**
Venezuela	New uncontrolled facility	0%	11%	14%	20%	**22.6%**
Venezuela	**Post-CDM facility**	**0%**	**0%**	**0%**	**0%**	**0%**

IV.8.2 Abatement Measures and Engineering Cost Analysis

One abatement option, thermal oxidation, is examined in this analysis of the HCFC-22 production sector; Table 8-3 and Table 8-4 provide a technology overview of this abatement measure. For more detailed information on the abatement measures considered for this sector see Appendix J.

Table 8-3: HCFC-22 Production Abatement Options

Abatement Option	Reduction Efficiency	Applicability
Thermal Oxidation	95%	Facilities with no abatement technology controls installed
		New facilities entering the market
		Facilities having previously participated in a CDM project

Table 8-4: Engineering Cost Data on a Facility Basis

Facility Type	Project Lifetime (years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO$_2$e)
Facilities with no abatement technology controls installed	20	$4,800,000	$0	$119,000	**5,932,661**
New facilities entering the market		$3,700,000			
Facilities having previously participated in a CDM project		**$0**			

IV.8.2.1 Thermal Oxidation

Thermal oxidation, the process of oxidizing HFC-23 to CO_2, hydrogen fluoride, and water, is a demonstrated technology for the destruction of halogenated organic compounds. For example, destruction of more than 99% of HFC-23 can be achieved under optimal conditions (i.e., a relatively concentrated HFC-23 vent stream with a low flow rate) (Rand et al., 1999). In practice, actual reductions will be determined by the fraction of production time that the destruction device is actually operating. Units may experience some downtime because of the extreme corrosivity of hydrogen fluoride and the high temperatures required for complete destruction. This analysis assumes a reduction efficiency of 95%.[2]

The destruction of HFC-23 by thermal oxidation is assumed to be 100% applicable to all facilities, and the analysis assumes a project lifetime of 20 years. Cost estimates for installing and operating a thermal oxidizer are summarized below:[3]

- **Capital Costs:** The capital cost for a thermal oxidation system is estimated to be approximately $4.8 million to install at an existing plant and $3.7 million to install as part of constructing a new plant (Irrgang, 2011).
- **Annual O&M Costs:** O&M costs are approximately 2% to 3% of total capital costs (Irrgang, 2011). This analysis assumes an annual cost that is 2.5% of total capital costs for facilities with no abatement technology control installed and just over 3% of total capital costs for new facilities that are entering the market.
- **Annual Revenue:** No annual savings or revenues are associated with the thermal oxidation abatement option.[4]
- **Technical Lifetime:** 20 years
- **Reduction Efficiency:** Thermal oxidation technology is assumed to be 95% efficient in abating HFC-23 emissions.

IV.8.2.2 Evaluation of Future Mitigation Options and Trends

This analysis evaluates how thermal oxidation can be applied to facilities that are current CDM participants after the crediting period is over and the CDM project is completed. Because an incineration device is already installed as a result of the CDM project, the costs to adopt the abatement measure relate only to its annual operation. Facilities participating in CDM are assumed to have completed their crediting periods by 2020.

This analysis also assumes that new facilities will enter the market to meet future global demand of HCFC-22. New facilities are assumed to enter the market once projected production for a non-Annex I country exceeds current plant capacities. According to industry, the costs of installing thermal oxidation systems in new plants are generally less expensive than the cost of installation at existing plants. This

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[2] A representative of a company that manufactures thermal oxidation systems stated that new systems are built using materials that better resist corrosion than the materials used in older systems. The representative indicated that such new systems were likely to experience very limited downtime, considerably less than 5% (Rost, 2006).

[3] Estimates developed for this analysis are based on communication with industry and best available industry assessments; actual costs of some systems could differ from these estimates.

[4] It should be noted that annual revenue is generated for participants of CDM projects; however, CDM projects are not assumed to be covering further abatement of emissions in this analysis.

analysis uses a capital cost for new facilities that is approximately 23% less than the cost of installation at existing facilities (Irrgang, 2011).

IV.8.3 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for HCFC-22 production sector.

IV.8.3.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at the three model facility types to calculate a break-even price for each option at each facility. As mentioned earlier, this analysis developed four potential model facilities to model the mitigation potential in this sector. These facilities included the following:

- **Residual Emissions:** These are facilities that have abatement controls in place already. All facilities in the Annex I countries and facilities that have CDM projects (mitigation projects funded by developed countries under the Kyoto Protocol) in the developing countries are considered "residual emission facilities."
- **Non-CDM and Uncontrolled Facility:** Non-CDM facilities are existing facilities that are uncontrolled. These facilities exist in China, South Korea, and Venezuela.
- **New Uncontrolled Facility:** New facilities are assumed to be uncontrolled when built. It is assumed that a new facility enters the market once projected production exceeds current capacity. In other words, the percentage of emissions from new facilities is 0% until projected production exceeds capacity. It is assumed that new facilities will only be built in non-Annex I countries.
- **Post-CDM Facility:** Similar to the "less mitigation scenario" of Miller et al. (2011), this analysis assumes that the 12 CDM projects that opted for a 7-year crediting period (in China, South Korea, Mexico, and Argentina) are not renewed after their first terms (note the remaining seven facilities opted for a one-time fixed crediting period that cannot exceed 10 years). Please see Section IV.8.4 for a discussion on the uncertainty and limitations regarding this assumption. Under this assumption, by 2020, all facilities previously controlled via CDM ("residual emission model facility") are considered a "post-CDM" facility. It is assumed that the incineration device installed (via a CDM project) will not be kept in operation once the CDM crediting period is over. This analysis costs out mitigation from these facilities differently than a new uncontrolled facility by taking into account that no capital costs will be needed to install the incinerator.

IV.8.3.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Market penetration rates vary over time as systems are upgraded in the future. Table 8-5 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of thermal oxidation for each facility type.

Table 8-5: Technical Effectiveness Summary

Model Facility Type	Technical Applicability	Market Penetration Rate (2030)	Reduction Efficiency	Technical Effectiveness (2030)
Non-CDM and uncontrolled facility	100%	100%	95%	**95%**
New uncontrolled facility	100%	100%	95%	**95%**
Post-CDM facility	100%	100%	95%	**95%**

IV.8.3.3 Estimating Abatement Project Costs and Benefits

Abatement project costs discussed in the previous section were used to calculate the break-even price for implementing the thermal oxidation technology at each facility type (excluding residual emission facilities). Using the engineering cost data discussed earlier, Table 8-6 presents the example break-even prices for each facility type.

Table 8-6: Example Break-Even Prices for Abatement Measures in HCFC-22 Production

Model Facility Type	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price ($\$/tCO_2e$)
Non-CDM and uncontrolled facility	5,932,661	0.16	0.02	0.03	0.15
New uncontrolled facility	5,932,661	0.12	0.02	0.02	0.12
Post-CDM facility	5,932,661	0.00	0.02	0.00	0.02

IV.8.3.4 MAC Analysis Results

The global abatement potential for HFC-23 reductions in HCFC-22 production sector is 255 $MtCO_2e$, which is approximately 89% of projected emissions in 2030. Table 8-6 presents the cumulative reductions achieved at selected break-even prices.

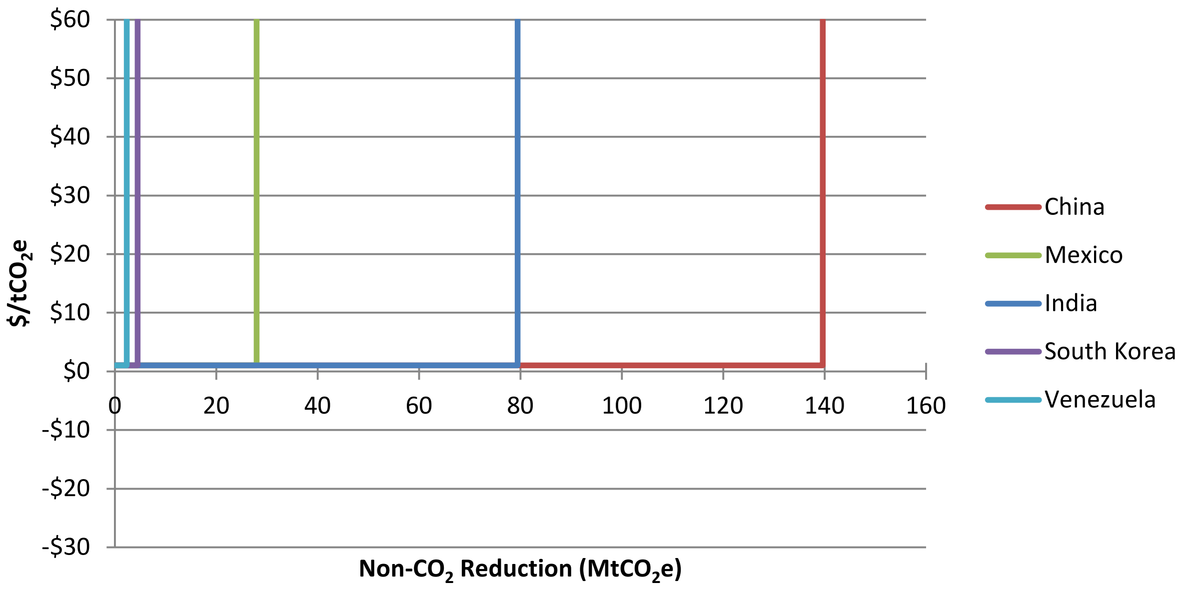
The results are driven largely by the designation of model facilities in different countries. For example, the United States and Russia have zero mitigation potential because they are included in the Annex I group of countries and were assumed to have 100% of their baseline emissions represented by the residual emission model facility (see Table 8-2).

Figure 8-4 shows the corresponding MAC curves for the six countries with abatement potential in 2030, which include China, India, Mexico, South Korea, and Venezuela. Total abatement potential is achieved at break-even prices between $\$0/tCO_2e$ and $\$1/tCO_2e$ in 2030, hence the "L" shape of the curves.

Table 8-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($/tCO2e)										
Country/Region	10	5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	—	139.7	139.7	139.7	139.7	139.7	139.7	139.7	139.7
India	—	—	—	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5
Mexico	—	—	—	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
South Korea	—	—	—	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Venezuela	—	—	—	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Rest of Region											
Africa	—	—	—	—	—	—	—	—	—	—	—
Central and South America	—	—	—	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Middle East	—	—	—	—	—	—	—	—	—	—	—
Europe	—	—	—	—	—	—	—	—	—	—	—
Eurasia	—	—	—	—	—	—	—	—	—	—	—
Asia	—	—	—	—	—	—	—	—	—	—	—
North America	—	—	—	—	—	—	—	—	—	—	—
World Total	—	—	—	**255.4**	**255.4**	**255.4**	**255.4**	**255.4**	**255.4**	**255.4**	**255.4**

Figure 8-4: Marginal Abatement Cost Curves for Countries with Abatement Potential in 2030



IV.8.4 Uncertainties and Limitations

This analysis examines a scenario in which the current CDM projects, including those projects with seven-year crediting periods, are completed by 2020.[5] Whether project renewals will occur is uncertain; it is also uncertain whether facilities would continue to abate even in the absence of CDM incentives. Although the first seven-year crediting period for the South Korean plant in Ulsan, which ended in December 2009, was recently renewed for another seven years by the CDM Executive Board in November 2011, the European Commission recommended in January 2011 that the EU cease the purchase of certified emission reductions (CERs) derived from emission mitigation of HFC-23 production after May 2013 (Europa, 2012). In addition to this ban, which has been formally adopted, other countries, such as New Zealand and Australia have announced that they will not accept CERs from HFC-23 destruction projects.

The projections in this analysis are limited to this scenario to examine mitigation costs in the absence of continued CDM projects post-2020; this analysis has not attempted to examine emission projections and MAC curves under a scenario where CDM projects are renewed post-2020.

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[5] This scenario is similar to the "Less Mitigation" scenario as presented by Miller et al. (2011).

References

Chemical and Economics Handbook (CEH). 2001. Fluorocarbons CEH Marketing Research Report. *Chemical and Economics Handbook.*

Europa. 2012. Emissions Trading: Commission Welcomes Vote to Ban Certain Industrial Gas Credits. Press release. Obtained at: http://europa.eu/rapid/pressReleasesAction.do?reference=IP/11/56. Accessed February 17, 2012.

Hufford, D., C. Newberg, D. Godwin, and E. Rim. 2012 "Benefits of Addressing HFCs under the Montreal Protocol." ASHRAE/NIST Ref Conf.

Irrgang, G. May 19, 2011. Personal communication between Gene Irrgang of Selas Linde and Veronica Kennedy of ICF International. Information provided by Mr. Rost to Ms. Ottinger in 2006 confirmed by Mr. Irrgang and adjusted for inflation.

McCulloch, A. and A.A. Lindley. 2007. "Global Emissions of HFC-23 Estimated to Year 2015." Atmos. Environ. 41:1560-1566.

Miller, B.R., and L.J.M. Kuijpers. 2011. "Projecting Future HFC-23 Emissions." Atmos. Chem. Phys. Discuss., 11: 23081-23102.

Miller, B.R., M. Rigby, L.J.M. Kuijpers, P.B. Krummel, L.P. Steele, M. Leiste, P.J. Fraser, A. McCulloch, C. Harth, P. Salameh, J. Mühle, R.F. Weiss, R.G. Prinn, R.H.J. Wang, S. O'Doherty, B.R. Greally, and P.G. Simmonds. 2010. "HFC-23 (CHF3) Emission Trend Response to HCFC-22 (CHClF2) Production and Recent HFC-23 Emission Abatement Measures." Atmos. Chem. Phys. 10: 7875-7890.

Montzka, S.A., L. Kuijpers, M.O. Battle, M.A.K. Verhulst, E.S. Saltzman, and D.W. Fahey. 2010. "Recent Increases in Global HFC-23 Emissions." Geophysical Research Letters. 37: L02808.

Rand, S., D. Ottinger, and M. Branscome. 1999. *Opportunities for the Reduction of HFC-23 Emissions from the Production of HCFC-22*. IPCC/TEAP Joint Expert Meeting. Petten, Netherlands, May 26–28.

Rost, M. April 24, 2006. Personal communication between Marc Rost of T-thermal and Debora Ottinger of the USEPA.

Rotherharn, D. 2004. *Greenhouse Gas Emission Reduction Verification Audit for Dupont's Louisville Works Freon®22 Plant, Final Report*. ICF Consulting, Toronto, Canada, Obtained at: http://cdm,unfccc.intipublicjnputs/inputamOOO llLetter DuponLAnnex2 03June04.pdf.

United Nations Environment Programme (UNEP). 2010. Data Access Centre. HCFC Production. Obtained at: http://ozone.unep.org/ Data Reporting/Data Access/.

UNFCCC. 2012. United Nations Framework Convention on Climate Change Flexible GHG Data Queries. Online Database Accessed: Spring 2012. Available at: http://unfccc.int/di/FlexibleQueries/Setup.do.

U.S. Environmental Protection Agency (USEPA). 2006. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020*. Office of Atmospheric Programs: Climate Change Division. Obtained at: http://www.epa.gov/ climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

Will, R., A. Kishi, and S. Schlag. 2004. CEH Marketing Research Report: Fluorocarbons. Chemical Economics Handbook. SRI Consulting, Menlo Park, California.

Will, R., and H. Mori. 2008. CEH Marketing Research Report: Fluorocarbons. Chemical Economics Handbook. SRI Consulting, Menlo Park, CA.

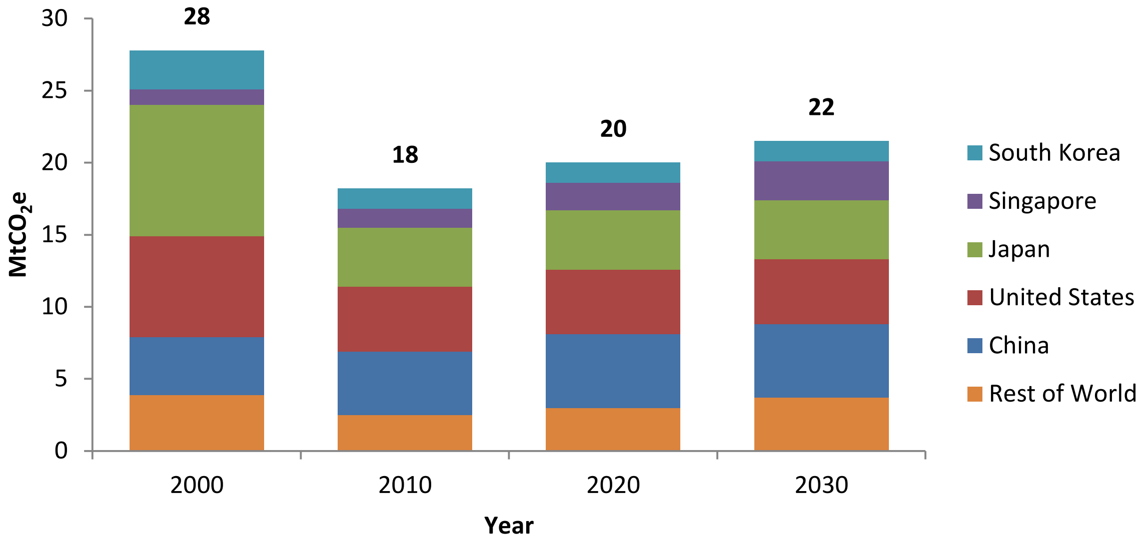
IV.9. F-GHG Emissions from Semiconductor Manufacturing

IV.9.1 Sector Summary

The semiconductor manufacturing sector uses several fluorinated greenhouse gases (F-GHGs) including sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), perfluorcarbons (PFCs) such as carbon tetrafluoride (CF_4) and perfluoroethane (C_2F_6), and the hydrofluorocarbon HFC-23 during fabrication, a portion of which are eventually emitted to the atmosphere. In addition, nitrous oxide (N_2O) and several fluorinated heat transfer fluids (HTFs) are used in the sector, but emissions from HTFs and N_2O are not included in this analysis.

Between 2000 and 2010 the production levels in the semiconductor manufacturing industry have rapidly grown, and the complexity of devices produced has advanced substantially. However, over this time period F-GHG emissions from this sector have declined (see Figure 9-1). This reduction can be attributed to ongoing mitigation efforts in response to voluntary emissions reduction goals set by the World Semiconductor Council (WSC). For 2010, the WSC set a quantitative emissions target below the baseline level, and for 2020 it has set an emissions rate target which will entail further implementation of mitigation technologies.[1]

Figure 9-1: Projected Baseline Emissions from Semiconductor Manufacturing: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012

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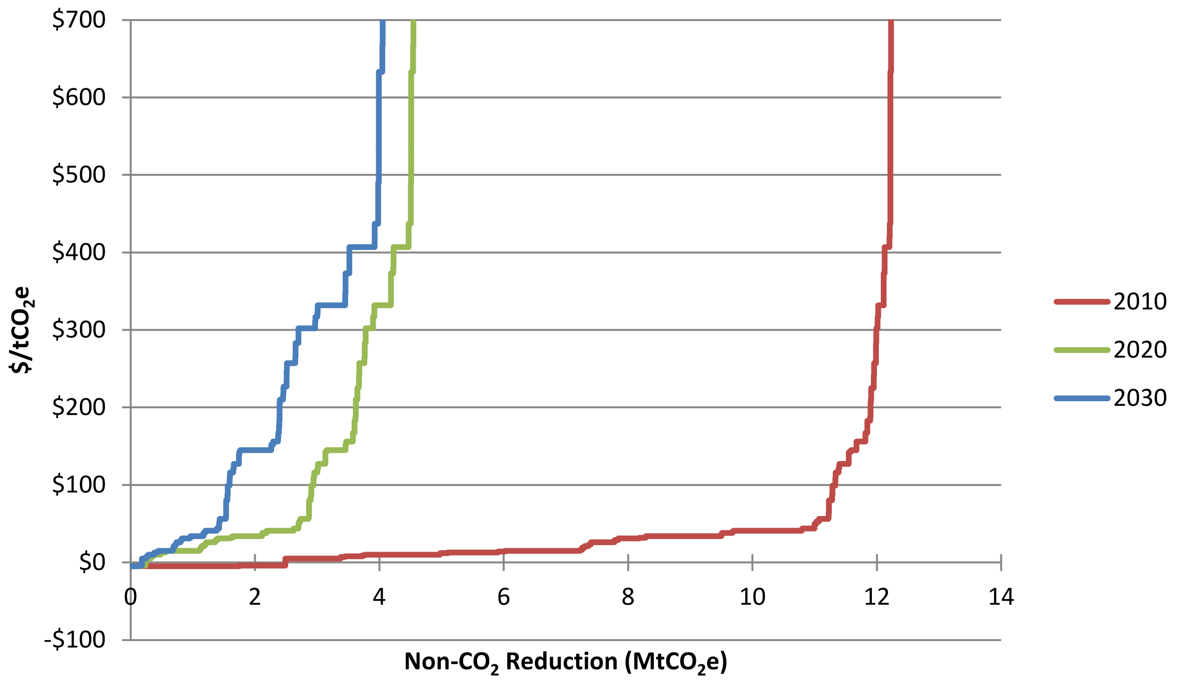
[1] The emissions projection baseline used here is based on the projection presented in USEPA (2012). That analysis was conducted before the details of the 2020 WSC voluntary commitment were available. The projection assumes a continuation of meeting an absolute emissions-level goal through 2030. Further analysis is needed to estimate future emissions as a result of the new normalized emission rate goal set by the WSC, which will depend on future production levels. More information on the specific assumptions in the baseline are available in USEPA (2012), and more information on the new WSC goal can be found at http://www.semiconductors.org/news/2013/05/28/news_2013/global_semiconductor_leaders_reach_agreement_on_plan_to_strengthen_industry_through_international_cooperation/

Six mitigation technologies are considered which reduce F-GHG emissions from semiconductor manufacturing: thermal abatement systems, catalytic abatement systems, plasmas abatement systems, the NF_3 remote chamber clean process, gas replacement, and process optimization. Significant implementation of these technologies is included in the baseline projection as part of meeting global voluntary targets. The following mitigation analysis is intended to characterize further reductions beyond this level, meaning that reductions are fewer and more costly than reductions would be applied to an uncontrolled baseline.

Mitigation costs and potentials for a particular facility depend on a variety of factors including the processes and gases used, and emissions reduction technologies already in use. The analysis in this chapter considers mitigation technologies applied to two stylized facilities: one representing a "new facility" with relatively new semiconductor technologies and processes and which has already implemented a suite of mitigation technologies, and one "old facility" which has relatively older semiconductor technologies and processes and limited existing use of emissions reduction technologies. Full details on the model facilities are in Section IV.9.4.2.

Global abatement potential of F-GHG emissions in semiconductor manufacturing is estimated to be 12 $MtCO_2e$ in 2010, 4.6 $MtCO_2e$ in 2020 and 4.2 $MtCO_2e$ in 2030. These abatement amounts correspond to 67%, 23%, and 20% respectively in 2010, 2020, and 2030. Figure 9-2 presents the sector marginal abatement cost (MAC) curves for these three years. The relative availability of potential further reductions below the baseline projections declines in later years because more mitigation technology is already included in the baseline as part of meeting voluntary reduction goals. In 2030, less than 1% of the technically feasible reductions could be supplied cost-effectively (at or below a zero break-even price), and nearly 7% of those reductions would be achievable at a carbon price of $50/$tCO_2e$.

Figure 9-2: Global Abatement Potential in Semiconductor Manufacturing: 2010, 2020, and 2030



This chapter begins by providing a brief discussion of activities and sources of F-GHG emissions in the semiconductor manufacturing process, and presents the projected emissions from 2010 to 2030. This is followed by an overview of the abatement measures available to the sector for achieving reductions, their technological parameters, and economic costs and benefits. The chapter concludes with a discussion of the MAC analysis and regional MAC results.

IV.9.2 Emissions from Semiconductor Manufacturing

Semiconductor manufacturing emissions considered in this analysis result from two main types of manufacturing processes used: the etching of substrates and the cleaning of chemical vapor deposition (CVD) chambers. In addition to direct emissions of portions of F-GHGs that are not consumed in these processes, by-product emissions of CF_4 and other gases (e.g., C_2F_6) occur when a fraction of the gases used in processes react to form other F-GHGs.

Other than etching and chamber cleaning, at least three other semiconductor manufacturing processes result in greenhouse gas emissions. This includes the use of F-GHGs in cleaning wafers, the use of nitrous oxide in chemical vapor deposition and other processes, and the use of fluorinated heat transfer fluids. However, these emitting processes were not considered in this analysis because there is very limited public information that would make estimating emissions from them feasible. In the future, if more quantitative information is gathered on these three emissive uses of F-GHGs, they can be considered in an updated analysis.

For the purpose of evaluating the cost of reducing F-GHG emissions from semiconductor manufacturing, this analysis considers the apparent differences in emissions resulting from newer and older manufacturing processes and mitigation practices; reduction costs for two typical fabrication facilities (fabs), which were generally characterized based on fab capacity (i.e., the number of manufacturing tools a typical fab may have); and the existing use of various mitigation technologies to etch and clean emissions. The emissions breakdown illustrated in Figure 9-3 represent emissions from these two types of fabs, further broken out by emission from etch and chamber clean processes. In 2020, new facilities are expected to make up 30% of global emissions, with old facilities accounting for the remainder. A description of the characteristics of the old and new fab considered for purposes of analysis is contained in Section IV.9.4.2.

IV.9.2.1 Activity Data or Important Sectoral or Regional Trends

Several important industry trends drive changes in emissions and mitigation potential from semiconductor manufacturing: 1) rapid production growth, 2) evolving manufacturing processes and increasing complexity in devices produced, and 3) impacts of mitigation efforts resulting from voluntary emissions reduction goals. These trends are described below.

Between 2001 and 2011, global semiconductor manufacturing, measured on the basis of total manufactured layer area (TMLA), indicates a compound annual growth rate of approximately 10% per year, which is higher than the silicon consumption growth rate of approximately 7% per year (VLSI, 2012 and WFF, 2012).[2] Both silicon area and TMLA are metrics of semiconductor production; however the difference in growth rate is driven by the increasing complexity of devices, as TMLA reflects

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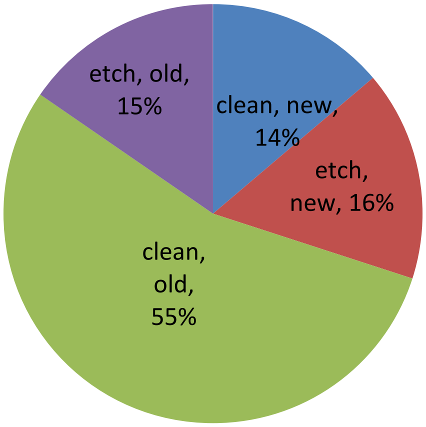
[2] Silicon consumption was taken from VLSI, 2012. TMLA was derived in the EPA PFC Emissions Vintaging Model using data from VLSI, 2012 and WFF, 2012.

Figure 9-3: Global F-GHG Emissions in 2020 by Fab Type and Process (% of GWP-Weighted Emissions)



the silicon wafer base layer plus all the metal interconnect layers and the silicon consumption reflects just the base. More recently production growth has slowed. Between 2006 and 2011, annual production growth is estimated to be about 5% on a TMLA basis, or 4% on a silicon area basis.

Etch and chamber-cleaning processes have evolved as semiconductor technologies have advanced and understanding of the emission pathways associated with manufacturing has improved. As technologies advanced, the semiconductor industry used larger wafer sizes to increase to increase chip production (e.g., 150 mm to 200 mm to 300 mm). Fabs that produce semiconductors on smaller wafers, on average, tend to be older and use manufacturing processes that result in a different breakdown of F-GHG emissions from etch and clean processes as compared to newer fabs. Older fabs may emit approximately 80% of F-GHG emissions total from chamber-cleaning processes and about 20% of emissions from etch processes. These percentages change to about 45%/55% clean/etch for newer fabs. This shift in the source of emissions over time is a result of the following: 1) newer fabs generally are trending to NF_3 remote-clean technologies that result in lower emissions on a CO_2e basis than traditional older C_2F_6- or C_4F_8-based clean systems, 2) more technologically advanced etch processes have a significantly greater number of steps, resulting in more F-GHG emissions, and 3) newer fabs can have less physical limitations on using abatement. As a new generation of fabs come online using 450 mm wafers, it is expected they will continue to use NF_3 remote clean technologies, abatement, and more advanced etch processes.

The WSC set an absolute emissions reduction goal for 2010 and a further emissions rate reduction goal for 2020. The 2010 WSC goal was an emission reduction of 10% relative to 1995 baseline F-GHG emissions.[3] This emission reduction goal was met in 2010. Achievement of the 2010 WSC emissions reduction goal has occurred in the context of significantly increasing underlying manufacturing activity. A 2011 joint WSC statement reported that the participating industry associations had achieved a collective 32% reduction from their baselines while semiconductor industry production increased roughly six times over the same time period (WSC, 2011).

In 2011, the WSC outlined a new voluntary F-GHG agreement for 2020 (WSC, 2011). This agreement sets a normalized emission rate goal of 0.22 $kgCO_2e/cm^2$, which is a 30% reduction from the 2010 WSC aggregate baseline emissions rate (including China, which was not included in the 2010 goal) of 0.33

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[3] Korea has a baseline year of 1998.

$kgCO_2e/cm^2$. In the 2020 voluntary goal the WSC also strongly suggests the use of best practices at newly built manufacturing facilities.[4] EPA has not yet analyzed how this new agreement would relate to absolute emission reductions in WSC countries, however achieving this goal would require significant use of mitigation technologies. The baseline used for this analysis assumes continued production growth and continued implementation of mitigation technologies; however it was estimated before the details of the 2020 WSC goal were available. Further analysis is necessary to estimate expected semiconductor manufacturing emission accounting for the 2020 WSC goal. Incorporating the new goal would likely result in somewhat reduced projected emissions in 2020 and somewhat increased projected emissions for 2030.

IV.9.2.2 Emissions Estimates and Related Assumptions

Projected emissions are based on estimated production level and capacity (described above), emissions rates drawn from voluntary reporting in the U.S., emissions as reported to the UNFCCC, and achievement of voluntary goal levels.

The preferred activity data to determine semiconductor emission estimates are gas consumption data. However, this information is not available globally. Instead, limited data on gas usage from the USEPA Voluntary Semiconductor Partnership was used to calculate emissions in relation to production. Therefore, emissions were estimated using this information, emission estimates from the UNFCCC, and alternative activity data, which is production capacity.

As described above, this analysis takes into account voluntary mitigation activities in the various WSC member countries and assumes that member countries maintain emissions at the goal level in the future. Projected emissions for major countries and regions are presented in Table 9-1.

Table 9-1: Projected Baseline Emissions from Semiconductor Manufacturing: 2010-2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR[a] (2010 2030)
Top 5 Emitting Countries						
United States	4.4	6.3	5.1	5.1	5.1	0.7%
China	4.5	4.5	4.5	4.5	4.5	0.0%
Japan	4.1	4.1	4.1	4.1	4.1	0.0%
Singapore	1.3	1.6	1.9	2.3	2.7	3.9%
South Korea	1.4	1.4	1.4	1.4	1.4	0.0%
Rest of Regions						
Africa	0.02	0.03	0.03	0.04	0.05	5.0%
Central and South America	—	—	—	—	—	—
Middle East	0.2	0.3	0.3	0.4	0.5	4.3%
Europe	1.7	1.7	1.7	1.7	1.7	0.0%
Eurasia	0.1	0.2	0.2	0.3	0.4	4.6%
Asia	0.4	0.5	0.6	0.8	1.0	5.4%
North America	0.02	0.02	0.02	0.02	0.03	3.0%
World Total	**18.2**	**20.6**	**20.0**	**20.7**	**21.5**	**0.8%**

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

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[4] Best practices, which will be continuously reviewed and updated by the WSC, can be found here: http://www.semiconductorcouncil.org/wsc/uploads/Final_WSC_Best_Practice_Guidance_26_Sept_201-2.pdf

To estimate potential for further reductions beyond the voluntary control levels included in the baseline emissions projection, emissions must be allocated between uncontrolled emissions and residual emissions remaining after control measures have been implemented. Specific information on current use of mitigation technologies is not available, so the degree of mitigation is inferred by considering two stylized model facilities: one where almost full mitigation is used and one where almost no mitigation is used, and from comparing emission rates for controlled and uncontrolled facilities as determined using data reported through EPA's Greenhouse Gas Reporting Program (USEPA, 2013) and information gathered during EPA's voluntary partnership with the semiconductor industry.

IV.9.3 Abatement Measures and Engineering Cost Analysis

Six mitigation technology options were considered for the semiconductor manufacturing sector: thermal abatement, catalytic abatement, plasma abatement, NF_3 remote chamber clean, gas replacement, and process optimization.

- **Thermal abatement**: These point-of-use abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through abatement systems with catalysts (e.g., CuO, ZnO, Al_2O_3) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma, in a point-of-use abatement system, is used to react with (thereby destroying or removing) F-GHGs from the process effluent stream.
- **NF_3 remote chamber clean**: Highly ionized NF_3 is used to clean chemical vapor deposition chambers. This process is very efficient (using ~98% of the gas in a process) resulting in lower emissions on a mass and CO_2 basis than traditional in-situ chamber clean processes that use approximately 20% to 50% of the gas in a process and have lower efficiencies (USEPA, 2010).
- **Gas replacement**: Higher global warming potential (GWP) gases are replaced with lower GWP gases, and in some cases more efficient gases (e.g., C_4F_8 may replace C_2F_6 in a traditional chamber-cleaning process).
- **Process optimization**: Processes are adjusted to become more efficient, using more gas within the process, and thus resulting in lower emissions.

These technologies reduce emissions from either etch or chamber-cleaning processes or in some cases both. Table 9-2 demonstrates the applicability of each mitigation technology to each process type. While in reality some of these technologies can be stacked, or used together (e.g., a process can be optimized and then abatement can be applied to that process), the cost and mitigation analysis does not model this situation.

Table 9-2: Semiconductor Manufacturing Abatement Options

Fab/Emissions Type	Thermal Abatement	Catalytic Abatement	Plasma Abatement	NF3 Remote Clean	Gas Replacement	Process Optimization
Reduction Efficiency	**95%**	**99%**	**97%**	**95%**	**77%**	**54%**
New fab						
Etch emissions	X	X	X			
Clean emissions	X			X		
Old fab						
Etch emissions	X	X	X			
Clean emissions	X			X	X	X

Table 9-3 presents a summary of the engineering cost data for each of the mitigation technologies.

Table 9-3: Engineering Cost Data on a Facility Basis

Abatement Option	Project Lifetime (years)		Capital Costs (2010 USD)		Annual Costs (2010 USD)		Abatement Amount (tCO_2e)	
	New	Old	New	Old	New	Old	New	Old
Thermal abatement	7	7	$11,403,942	$5,701,971	$657,723	$328,862	10,497	52,375
Catalytic abatement	7	7	$13,813,189	$6,906,594	$910,555	$455,277	n/a	11,851
Plasma abatement	7	7	$3,629,329	$1,814,664	$103,695	$51,848	n/a	11,612
NF_3 remote clean	22	11	$3,005,084	$9,200,867	$1,214,892	$3,374,861	1,166	41,002
Gas replacement	22	11	n/a	$1,180,000	n/a	$64,231	n/a	29,911
Process optimization*	22	11	n/a	$109,440	n/a	($129,071)	n/a	20,976

Note: Values in parentheses denote negative costs.

*Values listed as capital costs for process optimization represent one-time labor costs, not cost of capital.

IV.9.3.1 Thermal Abatement

Thermal abatement systems can be used to abate emissions from both etching and CVD chamber-cleaning processes by heating process effluent streams to high temperatures to remove or destroy F-GHGs. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in sub-fabs, particularly in older facilities. In addition, these systems require large amounts of cooling water, and the system's use results in regulated NO_x emissions. Thermal abatement systems are currently the most widely used abatement system in the semiconductor industry.

The engineering cost estimates for this technology are as follows:

- **Capital Costs:** Thermal abatement system capital costs cover the cost of the abatement unit with ducting and water recirculation ($157,000 per unit), hook-up costs ($35,550), and natural gas infrastructure costs ($35,550) (Fthenakis, 2001; Burton, 2003). One unit is needed per tool at a facility. The total facility capital cost ranges from $11.4 million for new fabs to $5.7 million for old fabs.
- **Annual Costs:** Annual operating costs per manufacturing tool, as presented in Table 9-4, are the same for both new and old fabs. Total annual costs (e.g., utilities) for a new fab are estimated to be $658,000 and $329,000 for an old fab. The higher capital and annual costs for new fabs are based on the fact that new fabs typically have larger manufacturing capacities (i.e., more tools) (WFF, 2011). Annual costs per tool are summarized in Table 9-4. The per-tool cost is the same for both new and old fabs.
- **Annual Revenue**: No financial benefits (e.g., cost savings) are associated with using this mitigation technology without outside policy or other drivers.
- **Reduction Efficiency:** This analysis assumes a 95% reduction efficiency (Fthenakis, 2001; Beu, 2005; USEPA, 2009).
- **Technical Lifetime:** Based on expert judgment, it was estimated that the average lifetime of this system, and other abatement systems discussed in this analysis, is 7 years.

Table 9-4: **Annual Cost per Tool for Thermal Abatement Systems**

Annual Cost Component	Cost (2010 USD)
Water/waste water/maintenance	**$2,370**
Consumables	**$5,330**
Electricity	**$2,610**
Natural gas	**$2,840**

Source: Burton, 2003.

IV.9.3.2 Catalytic Abatement

A catalytic abatement system uses a catalyst to destroy or remove F-GHG emissions from the effluents of both plasma etching and CVD chamber-cleaning processes. This type of abatement is applicable at most facilities, but there may be some space constraints as mentioned above for thermal abatement systems. Additionally, because these systems are based on destruction via catalyst, they must be process/stream specific to achieve the 99% emission reductions quoted in the literature and used in this analysis (Fthenakis, 2001; Burton, 2003).

Because catalytic destruction systems operate at relatively low temperatures, their use results in little or no NO_x emissions, and the required amounts of water are also low. Because of the high cost of catalyst replacement, these systems are the least widely used type of abatement (expert judgment).

Cost estimates for this technology are as follows:

- **Capital Costs.** Capital costs are associated with purchasing and installing the abatement systems (Burton, 2003). One unit costs $217,010, and the installation costs $59,250, leading to estimated costs of $6.9 million and $13.8 million for old and new fabs, respectively.
- **Annual Costs.** Facilities incur annual costs per tool for water ($3,790), waste chemicals ($60), catalyst replacement ($12,580), and electricity ($1,780) (Burton, 2003). A new fab incurs annual costs for catalytic abatement of $910,600, and an old fab incurs costs of $455,300.
- **Annual Revenue.** No cost savings are associated with this technology.
- **Reduction Efficiency:** The analysis assumes 99% reduction efficiency for catalytic abatement (Fthenakis, 2001).
- **Technical Lifetime:** Seven years.

IV.9.3.3 Plasma Abatement

These systems, which use plasma to remove or destroy F-GHGs, are applicable to etch processes in most facilities, with some physical space limitations. (These systems, though, are smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen (H_2), oxygen (O_2), water (H_2O), or methane (CH_4) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no GWP. After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of F-GHG molecules (Motorola, 1998).

A plasma abatement system is needed on each tool chamber. The costs of plasma abatement systems are developed using the following information:

- **Capital Costs:** The plasma abatement technology requires capital costs that cover the purchase and installation of the system, which total $41,500 per chamber, equating to one-time costs of $3.6 million for new fabs and $1.8 million for old fabs (Fthenakis, 2001; Burton, 2003).
- **Annual Costs:** Facilities with plasma abatement systems are estimated to incur annual operation costs of $1,190 per chamber, which includes general maintenance and use of the system. Total annual facility costs are $103,700 for new fabs and $51,800 for old fabs, based on the assumption that there are 3.5 chambers per etch tool and varying numbers of tools for new and old fabs (Fthenakis, 2001; Burton, 2003).
- **Annual Revenue:** As with other abatement technologies, the use of plasma abatement systems will not result in any cost savings.
- **Reduction Efficiency:** The emissions reduction efficiency of this option is estimated to be 97% (Fthenakis, 2001; Hattori et al., 2006).
- **Technical Lifetime:** 7 years.

IV.9.3.4 NF_3 Remote Chamber Clean

NF_3 remote chamber clean is an alternative cleaning technology that offers the benefit of having a particularly high (~98%) utilization rate of NF_3 (IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. NF_3 remote clean systems dissociate NF_3 using argon gas, and converting the source gas to active F-atoms in the plasma upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine (F_2), and other gases, most of which are removed by facility acid scrubber systems. The use of NF_3 remote clean systems is much more prevalent in newer fabs because the technology was not available when many older fabs were constructed.

Capital costs for NF_3 remote clean systems will differ for new and old fabs because of the "readiness" for NF_3 remote clean installation. "Readiness" consists of having the current infrastructure (e.g., duct work, hook-ups) for system installation. It was assumed that old fabs are do not have the current infrastructure to use NF3 remote clean, whereas new fabs do. Therefore, the capital costs for old fabs reflect the needed infrastructure changes for the fab.

Cost assumptions include the following:

- **Capital Costs:** Both facility types would incur capital costs for purchasing the NF_3 remote system and the additional necessary F_2 scrub for use after the chamber cleaning of the waste stream. The costs for system purchase for a new fab are estimated to be $3 million. Old fabs are assumed to not be "NF_3 ready," or in other words, these facilities are not assumed to have the current infrastructure to handle the direct installation of NF_3 remote systems. Therefore, old fabs also incur capital costs, in addition to system costs, associated with investments such as gas hook-ups and necessary hardware such as manifolds and valves in addition to the costs of the systems which are assumed to be already installed at new fabs. (These costs are detailed in Table 9-5.) The old fab costs are estimated to be $9.2 million.
- **Annual Costs:** Facilities operating NF_3 remote clean systems are subject to annual costs that include the purchase of larger volumes of gas (NF_3 versus traditional chamber-cleaning gases such as C_2F_6), general maintenance, and the cost of F_2 scrubs to remove the highly explosive gas from the effluent. Remote clean requires a lot of NF_3, so much so that NF_3 purchases are estimated to comprise anywhere from 25% to upward of 75% of annual facility gas consumption (expert judgment). New fab costs annually for NF_3 remote clean are estimated to be $1.2 million and to be $3.4 million for old fabs (Burton, 2003).

Table 9-5: Capital Costs per CVD Chamber for Making a Facility NF_3 Ready

Activity	Capital Cost (2010 USD)
Labor/gas hookup	**$3,980**
NF_3 manifold, valves, etc.	**$16,591**
Toxic monitor	**$7,700**
Stainless steel line (double walled)	**$10,310**

Source: Burton, 2003

- **Annual Revenue:** No cost savings are assumed to be associated with this technology.
- **Reduction Efficiency:** The analysis assumes this technology offers a reduction of 95% of emissions (Beu, 2005).
- **Technical Lifetime:** Once the remote clean systems are installed, they will last for the lifetime of a facility. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab and 22 years for a new fab.

IV.9.3.5 Gas Replacement

Gas replacement can be used to mitigate emissions from the traditional CVD chamber-cleaning process. This method can be applied in most facilities and has already been used throughout the industry in many instances. For this strategy, a lower GWP gas replaces a higher GWP gas. The most common replacement seen is using C_4F_8 to replace C_3F_8 or C_2F_6. In addition, the replacement gas (C_4F_8) is often used/consumed more efficiently during CVD chamber cleaning than the original gas C_2F_6 or C_3F_8, which, combined with the differences in GWP, yields lower emissions.

As with most other technologies considered in this analysis, there are no associated cost savings.

- **Capital Costs.** Facilities replacing C_2F_6 or C_3F_8 with C_4F_8 face a capital expenditure that reflects the aggregate cost of the C_4F_8 gas hook-up and an engineer's time cost for implementation. Based on the Clean Development Mechanism (CDM) number NM0317, the aggregated cost of equipment, C_4F_8 gas hook-up, and an engineer's time for implementation and installation is estimated to be $1.2 million for old fabs (the technology is not assumed to be used at new fabs).
- **Annual Costs.** Facilities face an annual cost that reflects the cost of replacing C_2F_6 or C_3F_8 with the more expensive C_4F_8. The costs of these gases, taken from CDM NM0303, are $35 per kilogram of C_2F_6, $26 per kilogram of C_3F_8, and $72 per kilogram of C_4F_8. Costs for old fabs were estimated to be $64,230, which is based on an average amount of gas consumed per facility. Gas consumption information was estimated based on USEPA Voluntary Partnership data, in which facility age and gas consumption relationships were not distinguishable.
- **Annual Revenue.** No cost savings are associated with this technology.
- **Reduction Efficiency:** The analysis assumes a reduction efficiency of 77% for this mitigation technology (CDM methods NM0289, NM303, NM0317, NM0335).
- **Technical Lifetime:** As with NF_3 remote clean, once a gas is replaced, the "new" process will last for the lifetime of a fab. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab.

IV.9.3.6 Process Optimization

Process optimization is the reduction in GHG emissions from a process by modifying or adding to the process recipe. Process optimization is considered to be only applicable for chamber cleans because these processes offer the opportunity for more flexibility than etch processes. Etch processes are typically developed to optimize production yield, and they are only adjusted to increase this yield; a company would not risk negatively impacting it (Beu, 2005; Fthenakis, 2001). Process gas optimizations for CVD clean processes can be implemented because adjustments to these processes are much less precise than etch processes. There is room to reduce emissions without affecting yield. Optimization of clean processes to reduce emissions usually results in small production gains but sometimes can result in large increases in efficiency.

Facilities optimizing processes incur labor costs of an estimated $109,440; it is assumed that old fabs incur this cost, while new fabs do not implement this technology due to their assumed use of NF3 remote clean for the majority of clean processes.

Details of the cost estimates for this technology include the following:

- **One Time Labor Costs:** Facilities' optimizing processes incur a one-time labor cost. Labor costs of $43 per hour were used for a materials engineer in the semiconductor industry based on BLS (2010) information and an estimated 2,560 hours of work, resulting in a total labor cost for each model facility of $109,440.
- **Annual Costs:** No annual costs are associated with process optimization for clean processes that are outside of business-as-usual (BAU) annual facility costs.
- **Annual Revenue:** Because process optimization involves adjusting a process to perform more efficiently, the cost savings associated with this option are due to a lowered amount of gas required to be purchased. For simplicity, the process considered in this analysis for this option was a C_2F_6 traditional chamber clean, and the related savings were estimated to be $129,070. As for the gas replacement annual cost, this number varies depending on the size of the facility. However, consumption information was only able to be estimated based on USEPA Voluntary Partnership data, in which facility age and gas consumption relationships were not distinguishable.
- **Reduction Efficiency:** Observed reduction efficiencies for abatement of C_2F_6 in the literature range from 10% to 56% (Beu, 2005) and as high as 75% (Fthenakis, 2001). For the purposes of this analysis, an average reduction efficiency of 54% was used, and we assumed the change in process is permanent over the life of a facility.
- **Technical Lifetime:** As with NF_3 remote clean, once a gas is replaced, the "new" process will last for the lifetime of a fab. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab.

IV.9.4 Marginal Abatement Cost Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for semiconductor manufacturing.

IV.9.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at two hypothetical facilities to calculate a break-even price for each option at each facility (new and old). This section presents detailed information on how each type of fab was defined in this analysis, and detailed information on how costs were built out for each mitigation technology.

IV.9.4.2 Definition of Model Facilities

For this sector, two fab types were considered: an old fab and a new fab. The differences between these two fabs are discussed in more detail below:

- **Old:** The old fab is intended to capture facilities that use smaller wafer sizes, such as 150 mm and below, as well as some older 200 mm manufacturing facilities (i.e., fabs built before 2000). This fab is expected to use less current manufacturing processes and produce less, in terms of silicon area. was estimated for this analysis, based emissions data reported through the U.S. EPA Greenhouse Gas Reporting Program, that a typical "old" fab breakdown of emissions on a CO_2e basis is approximately 20% etch emissions and 80% clean emissions. This is because older etch processes involve less GHG-using steps and more commonly use traditional chamber cleans with gases such as C_2F_6 as opposed to remote chamber cleaning processes. This fab is also expected to not use any abatement and only use minimal process optimization and gas switching. It was assumed that an old fab has an average of 30 tools with 3.5 chambers per tool.[5]
- **New:** The new fab type encompasses facilities that use larger wafer, such as 300 mm wafers. It is estimated, based again on emissions data reported through the U.S. EPA Greenhouse Gas Reporting Program, that the total emission breakdown for the new fab is approximately 55% etch emissions and 45% clean emissions. In contrast to the old fab, the new fab uses more recent etch processes that have comparatively many more GHG-using steps and the fab has higher production, in terms of silicon area.[6] Another process shift seen in newer fabs is the trend toward using NF_3 remote chamber cleans as opposed to traditional chamber cleans, which results in relatively lower cleaning emissions. New fabs are assumed to use NF_3 remote clean mainly, and have abatement on all etch processes and all in situ chamber cleaning processes. It was assumed that new fab facility has about 50 tools with 3.5 chambers per tool.

The emission breakdowns are essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process. One other important factor is facility size. Newer fabs tend to have relatively larger production capacities than older fabs, and this difference was taken into account in this analysis.

The facilities used represent two clearly defined and distinct types of facilities. These defined facilities represent two existing scenarios, a better existing mitigation case and a worse existing mitigation case, for semiconductor manufacturing fabs. Given the variety of mitigation options, there are facilities that exist that may be in the somewhere between the two scenarios modeled. For instance, some fabs may partially abate emissions as opposed to using full abatement or no abatement. These fabs were not explicitly considered in this analysis due to the uncertainty associated with developing assumptions about their current mitigation practices.

IV.9.4.3 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by manufacturing process (etch and clean) in addition to process-specific estimates of technical applicability and market penetration. The

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[5] CVD and etch tools generally vary between having three to four chambers.

[6] Although newer etch processes are more efficient (i.e., gas utilization is higher) than older processes, the relative number of GHG-using steps in more recent processes negates the potential benefit of higher utilization of gas when considering overall facility etch emissions.

split of etch to clean emissions is held constant for all years. The technical applicability and market penetration of mitigation technologies is held constant over time for new facilities as it is assumed these facilities are addressing emissions as much as possible already. Whereas, technical applicability and market penetration for old facilities varies over time as it is assumed that more action will need to be taken by older facilities to meet stated voluntary reduction goals. Table 9-6 presents the assumed distribution of annual facility-level emissions by process for each fab type.

Table 9-6: Percentage of Annual Emissions by Process and Fab Type

	Percentage of Total Annual Emissions	
Process	**New**	Old
Etch	54%	**22%**
Clean	46%	**78%**
Total	**100%**	**100%**

Table 9-7 and Table 9-8 report the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness at new and old fabs. The technical effectiveness is the weighted average of the abatement measures using the process emissions presented in Table 9-6 for each process as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency.

Table 9-7: Technical Effectiveness Summary for New Fabs (Constant Over Time)

	Etch (54%)		Clean (46%)			
Abatement Measure	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Thermal abatement	0%	0%	90%	50%	95%	**20%**
Catalytic abatement	0%	0%	0%	0%	99%	**0%**
Plasma abatement	0%	0%	0%	0%	97%	**0%**
NF_3 remote clean	0%	0%	10%	50%	95%	**2%**
Gas replacement	0%	0%	0%	0%	77%	**0%**
Process optimization	0%	0%	0%	0%	54%	**0%**

Table 9-8: Technical Effectiveness Summary for Old Fabs (in 2020)

	Etch (20%)		Clean (80%)			
Abatement Measure	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Thermal abatement	50%	90%	50%	15%	95%	**15%**
Catalytic abatement	50%	5%	0%	5%	99%	**1%**
Plasma abatement	50%	5%	0%	0%	97%	**1%**
NF_3 remote clean	0%	0%	100%	5%	95%	**4%**
Gas replacement	0%	0%	10%	40%	77%	**2%**
Process optimization	0%	0%	10%	40%	54%	**2%**

Technical applicability assumptions presented in Table 9-7 and Table 9-8 are intended to reflect the space limitations or preexisting process performance issues that are likely to be found at a fraction of all facilities, particularly old facilities, preventing the total implementation of the abatement measures. Assumed market penetration rates are based on cost (lower cost options will penetrate the market more) and expert knowledge of industry trends. For example, fabs tend to use thermal abatement more than the other technologies in their etching processes. In addition, it was assumed that because most new fabs already have NF_3 remote systems in place less market share would go to gas replacement and process optimization.

The technical effectiveness estimates are then multiplied by the share of total emissions for each facility type to estimate the abatement potential achievable under each abatement measure. For the purposes of this analysis we assume a 10/90 split in 2010 for the distribution of annual emissions coming from new and old fabs. In future years, we assume based on expert judgment the share of total emissions coming from new fabs increases by 10% each year to account for the use of best practices by WSC members, old fabs closing and changes in wafer size/technology demands.

IV.9.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.9.3 to calculate the break-even price for each mitigation option at both new and old fab facilities. Table 9-9 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Although new fabs have lower break-even prices for thermal, catalytic, and plasma abatement measures, old fabs have lower break-even prices for NF_3 remote clean, gas replacement, and process optimization because of their relatively smaller size. Note that process optimization is the only negative break-even price option because of its low one-time cost and relatively high annual cost savings.

Table 9-9: Example Break-Even Prices for Abatement Measures in Semiconductor Manufacturing

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price[a] ($\$/tCO_2e$)
New fabs					
Thermal abatement	41,199	85	14	24	**76**
Catalytic abatement	8,096	526	101	146	**481**
Plasma abatement	11,833	94	8	26	**76**
NF_3 remote clean	22,551	114	242	18	**338**
Gas replacement	6,240	36	10	6	**40**
Process Optimization	1,648	13	−78	2	**−68**
Old fabs					
Thermal abatement	22,802	103	17	29	**91**
Catalytic abatement	4,575	620	119	173	**567**
Plasma abatement	3,293	226	19	63	**182**
NF3 remote clean	37,768	75	107	18	**165**
Gas replacement	9,753	31	7	7	**30**
Process optimization	3,864	7	−33	2	**−28**

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

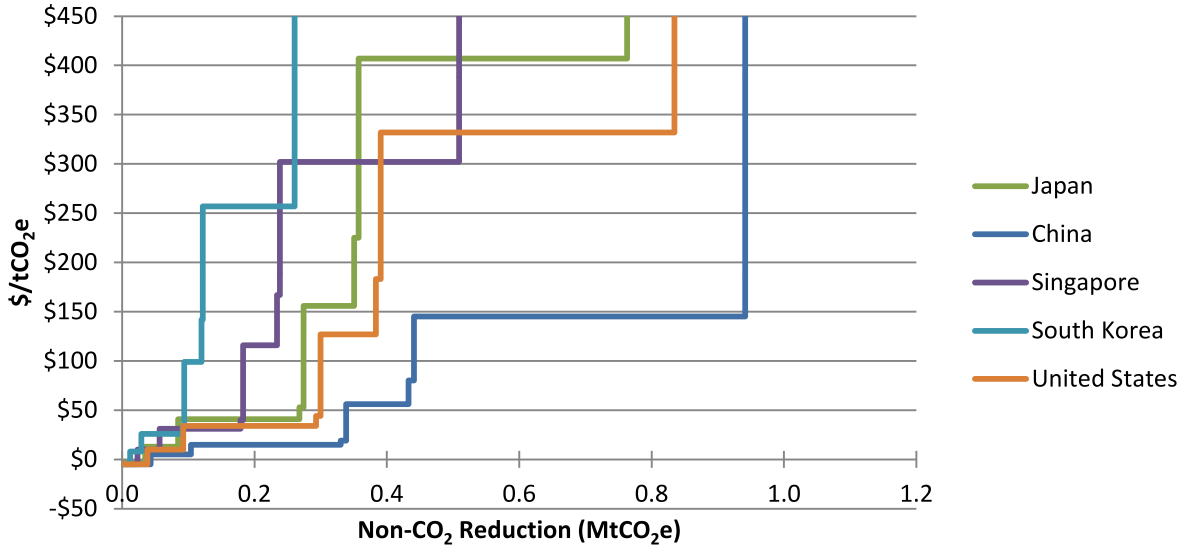
IV.9.4.5 MAC Analysis Results

The global abatement potential for F-GHG reduction in the semiconductor manufacturing sector is estimated to be 87% of total projected emissions in 2030. Table 9-10 presents the cumulative reductions achieved at selected break-even prices. Figure 9-4 shows the MAC curve for the top five emitting countries for this sector.

Table 9-10: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($/tCO₂e)										
Country/Region	10	5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	0.0	0.0	0.1	0.1	0.3	0.3	0.3	0.3	0.4	1.0
Japan	—	—	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.3	0.8
Singapore	—	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.5
South Korea	—	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.3
United States	—	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.3	0.3	0.9
Rest of Region											
Africa	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Central and South America	—										
Middle East	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Europe	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3
Eurasia	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Asia	—	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2
North America	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World Total	**—**	**0.1**	**0.2**	**0.2**	**0.4**	**0.7**	**0.7**	**0.8**	**1.4**	**1.6**	**4.2**

Figure 9-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



As stated earlier, early voluntary action by the semiconductor manufacturing industry resulted in a dramatic decrease in the level of F-GHG emissions emitted in 2010 and later years as compared with 2000. However, emissions are expected to grow from the current level based on increased demand for semiconductors over the next 20 years, and this may be particularly true in light of the new WSC normalized emission rate goal The MAC analysis suggests that additional reductions from this sector are costly. In the absence of any external climate policy drivers, major reductions in the semiconductor manufacturing sector would require a significantly high carbon price (>\$100/tCO_2e) to incentivize manufacturers to adopt additional mitigation options.

IV.9.5 Uncertainties and Limitations

A few key uncertainties exist with respect to the analysis for the semiconductor sector. The extent of current abatement is unclear; there is no comprehensive published information on the extent abatement systems are really in use in the industry. In addition, abatement system reduction efficiencies assumed in this analysis are really only achievable if the systems are properly operated and maintained, which may not always be the case. Also, abatement system reduction efficiencies may vary by gas (e.g., CF_4 is harder to abate than other F-GHGs because of its relatively high thermo-stability, or bond strengths). Finally, the pace at which the semiconductor manufacturing sector has advanced has been historically very fast-paced. This continues to be true, but it cannot be certain that this will continue to be true given the continued rising costs of advancement.

The limitations to this analysis are that it could not consider the full picture of emissions from semiconductor manufacturing (e.g., heat transfer fluid emissions are not included), and that the new WSC normalized emission rate goal was not known at the time of the analysis.

References

Applied Materials. 1999. *Catalytic Abatement of PFC Emissions*. Presented at Semicon Southwest 99: A Partnership for PFC Emissions Reductions, October 18, 1999, Austin, TX.

Beu, L. 2005. "Reduction of Perfluorocarbon (PFC) Emissions: 2005 State-of-the-Technology Report." TT#0510469A-ENG. International SEMATECH Manufacturing Initiative (ISMI), Albany, New York. December 2005. Obtained at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/final_tt_report.pdf.

Bureau of Labor Statistics. 2010. Overview of BLS Wage Data by Area and Occupation. Available at: http://bls.gov/bls/blswage.htm

Burton, S. 2003. Personal communication with Brown of Motorola (2002) supplemented by personal communication with Von Gompel of BOC Edwards (2003), research of DuPont's Zyron Web site (2003), and personal communication with Air Liquide regarding thermal destruction, NF_3 remote clean, and capture membrane unit costs.

Fthenakis, V. December 2001. *Options for Abating Greenhouse Gases from Exhaust Streams.* Brookhaven National Laboratory. Obtained at: http://www.bnl.gov/isd/documents/23784.pdf.

Hattori et al., 2006. "Application of Atmospheric Plasma Abatement System for Exhausted Gas from MEMS Etching Process." Presetned at the Institute of Electrical and Electronics Engineers International Symposium on Semiconductor Manufacturing 2006, Tokyo, Japan, September 25-27, 2006 .

Intergovernmental Panel on Climate Change (IPCC). 2006. 2006 *IPCC Guidelines for National Greenhouse Gas Inventories.* The National Greenhouse Gas Inventories Programme (Volume 3, Chapter 6: Electronics Industry Emissions), The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Motorola. October 18, 1998. *Long-Term Evaluation of Litmus "Blue" Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement*. Presented at Semicon Southwest 99: A Partnership for PFC Emissions Reductions, Austin, TX.

U.S. Environmental Protection Agency (USEPA). 2009. Developing a Reliable Fluorinated Greenhouse Gas (F-GHG) Destruction or Removal Efficiency (DRE) Measurement Method for Electronics Manufacturing: A Cooperative Evaluation with IBM (EPA 430-R-10-004), Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC. Available at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/ibm_report.pdf.

U.S. Environmental Protection Agency (USEPA). 2010. *Draft Emission Factors for Refined Semiconductor Manufacturing Process Categories.* Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC. Available in docket EPA-HQ-OAR-2009-0927.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). (2013). Data from the Greenhouse Gas Reporting Program. 40 CFR Part 98. Washington, D.C. Available at: http://www.epa.gov/ghgreporting/ghgdata/

VLSI, 2012.VLSI Research, Inc. (2012) Worldwide Silicon Demand. August 2012.

WSC, 2011. *Joint Statement of 15th Meeting of the World Semiconductor Council (WSC)*. Resulting from the World Semiconductor Council in Fukuoka, Japan. May 26, 2011.

Bartos, Scott, Kshetry, Nina, and C. Shepherd Burton. 2007. Modelling China's Semiconductor Industry Fluorinated Compound Emissions and Drafting a Roadmap for Climate Protection. Obtained at: http://www.climatevision.gov/sectors/semiconductors/pdfs/ISESH_2007_Final.pdf

Brown et. al., 2012. "Catalytic technology for PFC emissions control." Solid State Technology. Obtained at: http://www.electroiq.com/content/eiq-2/en/articles/sst/print/volume-44/issue-7/features/emissions-control/catalytic-technology-for-pfc-emissions-control.html. Accessed August 2012.

Molina, Wooldridge, and Molina. 1995. *Atmospheric Geophysical Research Letters* 22(13).

Other Sources Reviewed for this Analysis:

- Semiconductor Equipment and Materials Industry. 2011 World Fab Forecast, May 2011 Edition.
- Semiconductor Equipment and Materials Industry. 2012 World Fab Forecast, August 2012 Edition.
- WSC, 2012. *Joint Statement of 16th Meeting of the World Semiconductor Council (WSC).* Resulting from the World Semiconductor Council in Saratoga Spring, New York, United States. May 24, 2012.

Clean Development Mechanism Proposed Methodologies Reviewed:

- NM0289: PFC gas emission reduction by gas replacement for CVD cleaning at 200 mm (8 inches) process by Hynix Semiconductor Inc. (submitted September 2008)
- NM0303: PFC gas emissions reduction by gas replacement for CVD cleaning processes in semiconductor processing operations (submitted April 2009)
- NM0317: Substitution of fluorinated compound (FC) gases for cleaning CVD reactors in the semiconductor industry (submitted June 2009)
- NM0330: Substitution of fluorinated compound (FC) gases for cleaning CVD reactors in the semiconductor industry (submitted December 2009)
- NM0332: PFCs emission reduction from installation of an abatement device in a semiconductor manufacturing facility (submitted January 2010)
- NM0335: PFC emission reduction by gas replacement in the process of CVD cleaning in semiconductor production (submitted February 2010)

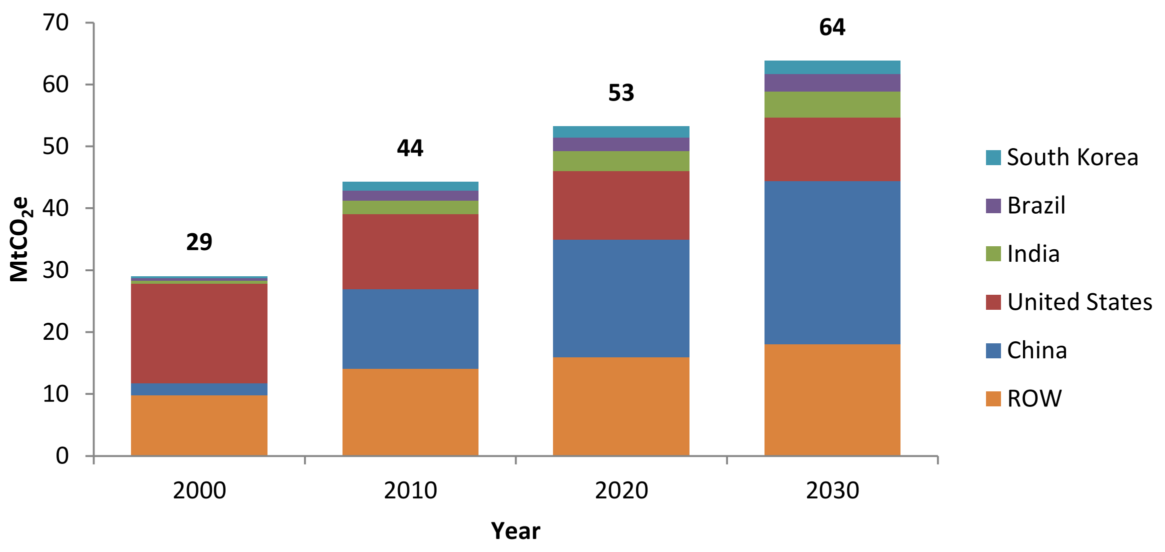
IV.10. SF_6 Emissions from Electric Power Systems

IV.10.1 Sector Summary

Electric utilities use transmission and distribution equipment that contains sulfur hexafluoride (SF_6). Equipment insulated with SF_6 is most frequently found at electrical substations. Emissions of SF_6 occur as a result of leaking equipment and improper handling practices during servicing and disposal.

Global SF_6 emissions from electric power systems (EPSs) are expected to increase through 2030, reaching 64 million metric tons of carbon dioxide equivalent ($MtCO_2e$) (see Figure 10-1). In these projections, China represents a significant share of total emissions by 2030. Brazil, India, South Korea, and the rest of world increase their SF_6 emissions marginally, while the United States experiences a decline over the same time period.

Figure 10-1: SF_6 Emissions from Electric Power Systems: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012

The following technologies and handling practices can be implemented to reduce both causes of emissions—leaking equipment and improper handling:

- **Leak detection and leak repair (LDAR)**: Various monitoring and repair methods reduce gas leakage from gaskets and faulty seals in equipment.
- **Equipment refurbishment**: Refurbishing old equipment reduces longer-term leakage problems that cannot be addressed sufficiently by LDAR.
- **SF_6 recycling**: Technicians transfer SF_6 to special gas carts prior to maintenance or decommissioning, reducing emissions that would otherwise result from the venting of SF_6 to the atmosphere.
- **Improved SF_6 handling**: Employee training efforts that improve general handling practices of SF_6 to reduce and avoid instances such as accidentally venting the gas, using inappropriate

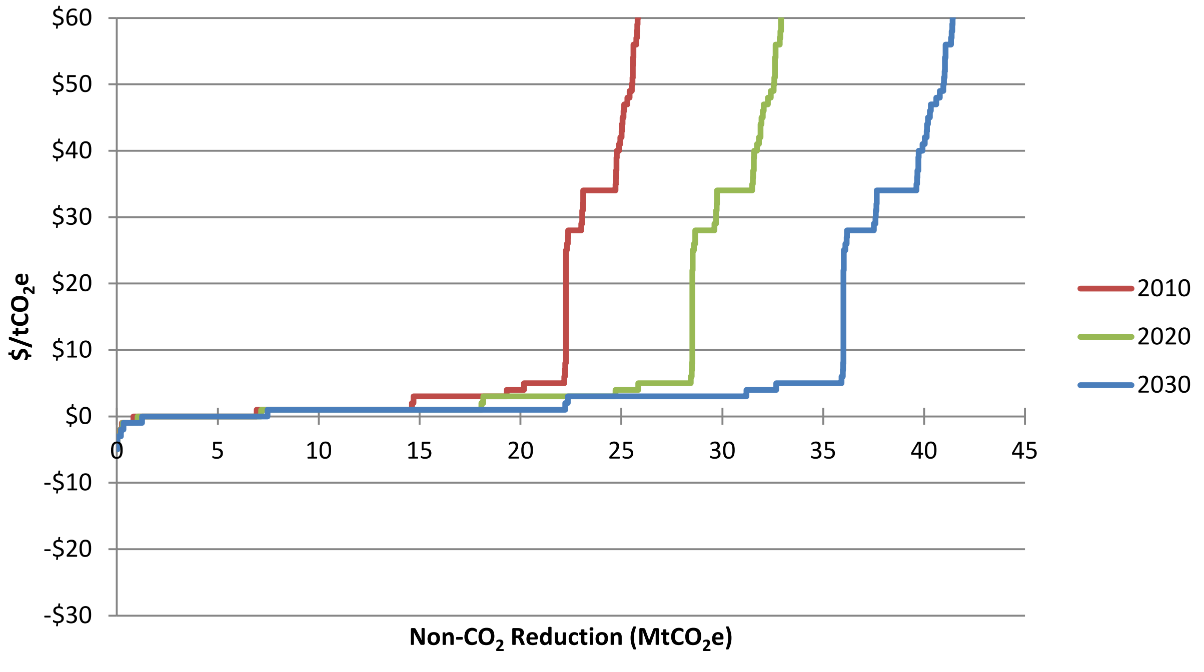
fittings to connect transfer hoses to cylinders or equipment, misplacing gas cylinders, and other similar situations that result in handling losses.

Europe and Japan have largely adopted emission reduction measures to the greatest extent possible; it is believed that few opportunities remain for reduction; data reported to the UNFCCC indicate a downward trend of emissions within the last decade (UNFCCC, 2009). In the United States, SF_6 recycling is widely used, but there remains significant potential for reductions through other measures, particularly improved SF_6 handling. In the developing world, SF_6 recycling is rarely conducted; therefore, there are significant opportunities for reductions from increased SF_6 recycling in addition to significant reduction opportunities from improved SF_6 handling (NCGC, 2010; NEPA, 2005). The most cost-effective reductions can be achieved by improving general SF_6 handling practices at EPSs in the developing world. In these cases, the cost per ton is −\$1.20/tCO_2e. The most expensive emission reductions for the developing world are from implementing LDAR at \$1.98/tCO_2e. Opportunities to reduce emissions in the United States are more expensive, expected to range from −\$0.20/tCO_2e for improved SF_6 handling to \$9.40/tCO_2e for equipment refurbishment.

The manufacture of equipment for electrical transmission and distribution can also result in SF_6 emissions, but this type of emission is not included in this assessment.

The global abatement potential in the EPS sector is 42.8 $MtCO_2e$ in 2030, which represents 67% of projected baseline emissions. This represents the maximum level of reductions that are technically achievable by applying the four abatement measures in the EPS sector. For example, leak detection and leak repair is assumed to have a reduction efficiency of 50%, and is applied only to a the stream of emissions that occur due to periodic leakage; other options have a greater reduction efficiency, but no options are available to reduce 100% of emissions from all emission streams. Figure 10-2 presents the global marginal abatement cost (MAC) curves charting the potential emission reductions in 2010, 2020, and 2030.

Figure 10-2: Global Abatement Potential in Electric Power Systems: 2010, 2020, and 2030



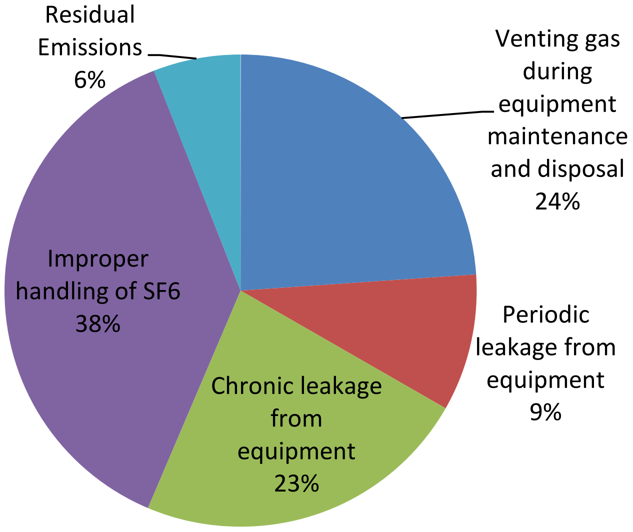
In 2030, approximately 7.5 $MtCO_2e$, or a 12% reduction in baseline emissions, is technically achievable at a break-even price of $0/$tCO_2e$. At $5/$tCO_2e$, an additional 28 $MtCO_2e$ may be reduced, equating to a cumulative reduction of 56% of the global emissions baseline. The remaining reductions of 7 $MtCO_2e$ are available at incrementally higher prices.

In the following sections of this chapter, we first characterize the source of SF_6 emissions in the EPS sector and the trends driving future emissions projections. Next, we discuss the projected baselines from 2010 to 2030. This is followed by a description of the abatement measures' engineering and cost assumptions assumed for this analysis. Section IV.10.4 presents the additional assumptions used in the MAC analysis unique to the EPS sector. The final section presents the MAC results in more detail and discusses some of the uncertainties and limitations to the analysis.

IV.10.2 SF_6 Emissions from Electric Power Systems

Emissions of SF_6 from electrical equipment used in EPSs broadly occur through two routes: equipment leakage and handling losses. Leakage losses can occur at gasket seals, flanges, and threaded fittings and are generally larger in older equipment. Emissions from improper handling can include intentional venting to the atmosphere or unintentional venting, such as transferring SF_6 between containers and equipment using improperly attached or improperly sized fittings. Figure 10-3 presents the global distribution of SF_6 emissions by emission stream assumed for this analysis. Leakage losses correspond to periodic leakage from equipment (9%) and chronic leakage from equipment (23%). Improper handling and venting losses correspond to venting gas during equipment maintenance and disposal and improper handling. The break-out percentages are based on assumptions used to develop the technical applicability of the options identified to mitigate these emission streams.

Figure 10-3: Percentage of Global SF_6 Emissions in 2020 by Emission Stream (% of GWP-Weighted Emissions)



The amount of SF_6 gas that each piece of electrical transmission and distribution equipment can hold when properly insulated is referred to as "nameplate capacity," which is measured in pounds or kilograms of the gas. For the purpose of evaluating the cost of reducing SF_6 emissions from EPSs, this analysis considers reduction costs for a typical electric transmission and distribution system that uses SF_6-insulated electrical equipment totaling 100,000 pounds of nameplate capacity. The system includes a variety of SF_6-insulated electrical equipment (including circuit breakers, circuit switchers, and gas-insulated substations), although the vast majority of SF_6 is contained in high voltage circuit breakers. Circuit breakers within the system are assumed to be produced by ABB, Alstom, HVB AE, Mitsubishi, and Siemens, with an equal proportion of breakers from each manufacturer.

The analysis considers several possibilities for the maintenance and SF_6 handling procedures used at the typical electric transmission and distribution system, reflecting different levels of emissions. For the purpose of this analysis, the three types of systems include the following:

- **Residual emissions system**: In Europe and Japan, abatement options are close to fully implemented. Therefore, a residual emissions system represents an EPS containing SF_6-insulated equipment located in Europe or Japan.
- **Uncontrolled system**: In contrast, abatement options have only been minimally applied or not applied at all in most developing countries (Czerepuszko, 2011a; NCGC, 2010; NEPA, 2005; Rothlisberger, 2011a). Therefore, the uncontrolled abatement system represents an EPS containing SF_6-insulated equipment located in a developing country, which for this analysis would mean any country outside of Europe, Japan, and the United States.[1]
- **Partially controlled system**: Abatement options have been partially to fully applied in the United States.[2] The partially controlled system represents an EPS containing SF_6-insulated equipment located in the United States.

Figure 10-4 displays the breakdown of global emissions by system type as projected for 2020. For the purpose of this analysis, the uncontrolled systems and partially uncontrolled systems are representative of every system within their identifying regions. Therefore, the engineering cost results will not vary among systems within the developing world or among systems within the United States.

IV.10.2.1 Activity Data or Important Sectoral or Regional Trends

The key activity data that drives SF_6 emissions from EPSs is the amount of SF_6-insulated electrical equipment in use; this quantity is important for both leakage and handling losses.

However, data are not available on the total amount of SF_6-insulated equipment currently in use or historically in use at the country level. In the absence of such data, changes in the amount of SF_6-insulated electrical equipment in use (both historically and in the future) can be estimated from the historical and projected changes in electricity demand at the regional level. This is because electricity demand is correlated with the size of the electrical grid required to service that demand, and the size of the electrical grid is correlated to the amount of SF_6 consumed by utilities within the region. Thus, the key activity data used to drive emissions is electricity demand. Other important activity data include the characteristics of the equipment in use (such as age) to estimate leakage emissions and employee training and investments in SF_6 handling technologies to estimate handling emissions. In this analysis, these drivers are addressed on a regional level.

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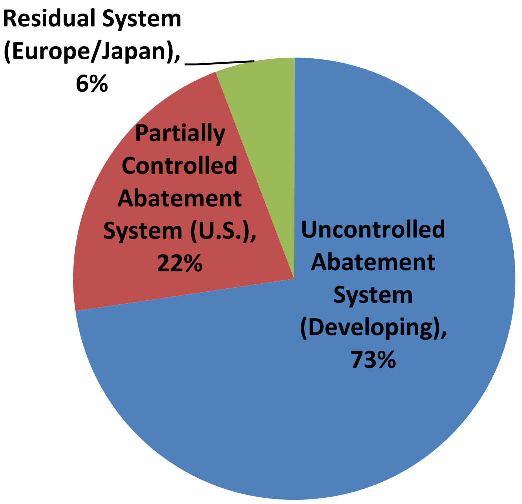
[1] Australia and New Zealand are considered to have uncontrolled systems, which may be one limitation to this assumption.

[2] This system is also assumed for Canada.

Figure 10-4: Global SF_6 Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



According to EIA (2009), electricity demand through 2030 is projected to grow two to three times faster in developing countries than developed countries.

Leakage Emissions

Over the past 30 to 40 years, the amount of SF_6 necessary for the operation of switchgear has declined significantly and the tightness of equipment has improved. Such engineering design changes have resulted in smaller leakage amounts and less frequent leakage over time (McCracken et al., 2000; Rhiemeier et al., 2010). The average age of SF_6-insulated equipment in developed countries (including Europe, Japan, and the United States) is considerably older than in developing countries. Until recently, developing countries were slow to adopt SF_6-insulated equipment because of its relatively high cost compared with other traditional technologies, such as oil-insulated circuit breakers (Rothlisberger, 2011b). Also, the electrical grid in developing countries has grown rapidly over the last decade with economic growth, so the average age of all types of electrical equipment tends to be newer in developing countries than in developed countries, whose electrical grid has historically grown at a more gradual pace. The average SF_6-insulated circuit breaker in developing countries, therefore, is assumed to leak less than the average SF_6-insulated circuit breaker in developed countries.

Handling Emissions

Employee training and investments in SF_6 handling technologies (such as SF_6 recovery carts) vary widely among countries and regions. The use of equipment and accessories to properly handle SF_6 is high in developed countries (Rothlisberger, 2011a) yet low to nonexistent in at least some developing countries (NCGC, 2010; NEPA, 2005). Employee training is perhaps strongest in Europe, where the European Commission requires that personnel who handle SF_6 receive formal training and certification (EC Reg. No. 842/2006). In the United States, employee training has improved significantly since 1999 by companies participating in the USEPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems, but, in general, training is not as rigorous as in Europe, and it is uncertain what level of training (if any) has been instituted by companies not part of the USEPA voluntary program. Employee training is low to nonexistent in at least some developing countries (NEPA, 2005).

IV.10.2.2 Emission Estimates and Related Assumptions

Global SF_6 emissions from EPSs in 2010 were estimated to be 44 $MtCO_2e$, which represents a 10% decrease from 1990 levels. This emissions decline, despite increases in the amount of SF_6 in use over the same time period, was based largely on improved management practices and the retirement of old leak-prone equipment in the United States and EU. However, it is estimated that emissions have increased in recent years because of the rapid increase in the amount of SF_6-insulated equipment being used in the developing world without the application of SF_6 abatement technologies and practices. These emission increases have been offset somewhat by the improved design of modern SF_6-insulated equipment being installed in the developing world. But from 2010 to 2030, global SF_6 emissions from EPSs are still projected to increase 44% from 44 to 64 $MtCO_2e$ (see Table 10-1), driven largely by increases in emissions from developing countries in Asia.

Table 10-1: Projected Baseline Emissions from Electric Power Systems: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGRa (2010-2030)
Top 5 Emitting Countries						
China	12.8	15.6	18.9	22.7	26.3	3.7%
United States	12.1	12.1	11.1	10.8	10.3	−0.8%
India	2.2	2.7	3.2	3.7	4.2	3.3%
Brazil	1.6	1.9	2.2	2.5	2.8	2.7%
South Korea	1.4	1.6	1.8	2.0	2.2	2.3%
Rest of Region						
Africa	1.7	2.0	2.3	2.5	2.8	2.4%
Central and South America	1.4	1.4	1.5	1.6	1.7	1.2%
Middle East	2.0	2.2	2.5	2.8	3.1	2.2%
Europe	3.6	3.3	3.1	2.5	2.1	−2.6%
Eurasia	1.1	1.1	1.1	1.1	1.1	0.0%
Asia	3.4	3.8	4.4	4.9	5.7	2.6%
North America	0.9	1.1	1.2	1.3	1.5	2.4%
World Total	**44.2**	**48.8**	**53.2**	**58.4**	**63.8**	**1.8%**

[a] CAGR= Compound Annual Growth Rate
Source: USEPA. 2012

Historical emission estimates of SF_6 from electrical equipment use are available for most developed countries through the UNFCCC flexible query system (UNFCCC, 2009). In the absence of UNFCCC reported data, historical global emissions were estimated using the 2004 RAND survey (Smythe, 2004) of global SF_6 sales to electric utilities and estimates of net electricity consumption by region. This method assumes that purchases of SF_6 by electric utilities are equal to emissions of SF_6 by utilities and that a country's share of global emissions is equal to the country's share of global electricity consumption.[3] Emissions projections are based on projected changes in electricity demand (EIA, 2009) for the country's

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[3] The assumption that SF_6 purchases are equal to emissions is conservative in that some EPSs purchase SF_6 to fill new equipment rather than to replace SF_6 lost through emissions.

region; as described above, changes in electricity demand correlate to changes in the electrical grid, which correlate to changes in SF_6 emissions.

IV.10.3 Abatement Measures and Engineering Cost Analysis

The four abatement options for this sector are SF_6 recycling, LDAR, equipment refurbishment, and improved SF_6 handling. Replacing existing SF_6-insulated equipment with newer equipment that holds less SF_6 and is more leak-tight is another possible abatement option; however, this mitigation practice is assumed to already occur in the baseline. Given that the investment to replace a circuit breaker or other SF_6-containing equipment can be as high as a million to several million dollars, it is not examined in this analysis for systems located in developing countries. All options are applicable to EPSs that are subject to abatement (those outside of Europe and Japan). For the purpose of this analysis, four distinct emission streams were analyzed for the sector, and each emission stream can only be abated by one of the abatement options (the abatement options are not capable of abating emissions for any of the other streams). Hence, the application of an abatement option to its unique emission stream does not affect the applicability of any other options to their own emission streams. Table 10-2 shows the reduction efficiency used for each abatement option.

Table 10-2: EPS Abatement Options

Abatement Option	Applicable System Types	Reduction Efficiency
SF_6 Recycling	Uncontrolled abatement system	90%
	Partially controlled system	
LDAR	Uncontrolled system	50%
	Partially controlled system	
Equipment Refurbishment	Uncontrolled system	95%
	Partially controlled system	
Improved SF_6 Handling	Uncontrolled system	90%
	Partially controlled system	

Table 10-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

The characteristics, applicability, and key engineering cost results for each abatement option are presented below. For additional information on these technologies see Appendix K.

IV.10.3.1 SF_6 Recycling

This option involves transferring SF_6 from electrical equipment into storage containers during equipment servicing or decommissioning so that the SF_6 can be reused. Recycling is conducted using an SF_6 reclamation cart (commonly referred to as a gas cart). The gas cart recovers the SF_6 from the equipment and purifies it for future use; the recovered and purified SF_6 gas can then be stored within the cart, in a separate storage container, or transferred back to the equipment for reuse. Proper recycling techniques are documented in technical literature (CIGRE, 2005; IEC, 2008; IEEE, 2012). The alternative to using a gas cart is venting the used SF_6 into the atmosphere and then replacing it with fresh SF_6. Venting is typically performed in areas where environmental consideration is low because the cost of purchasing new gas is often cheaper than purchasing gas carts and paying technicians to reclaim gas from equipment.

Table 10-3: Engineering Cost Data on a Facility Basis

Abatement Option	Project Lifetime (Years)	Capital Cost (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
SF_6 Recycling	15	$479,560	$67,994	$5,372	46,833
		$71,934	$6,256	$19,937	8,618
LDAR	5	$95,420	$12,592	$534	8,673
		$91,485	$3,476	$6,339	4,788
Equipment Refurbishment	20	$126,069	$9,570	—	6,591
		$453,849	$5,283	—	7,278
Improved SF_6 Handling	1	$13,526	$90,659	$253	62,444
		$13,526	$25,025	$2,508	34,474

The SF_6 recycling option addresses emissions that occur if SF_6 contained inside equipment is vented directly to the atmosphere, either because the equipment is undergoing a maintenance/repair activity requiring removal of the gas or because the equipment is being decommissioned. Based on expert judgment, SF_6 vented to the atmosphere accounts for 30% of emissions from uncontrolled systems (in developing countries) and 10% of emissions from partially controlled systems (in the United States).

SF_6 recycling can reduce emissions by 4,320 pounds for the uncontrolled systems and 795 pounds for the partially controlled systems. The lifetime of this abatement option is 15 years (Rothlisberger, 2011a). Cost and revenue estimates for the SF_6 recycling option are summarized below:

- **Capital costs.** The average total capital costs associated with the purchase of gas carts were estimated to be about $480,000 for the uncontrolled system and $72,000 for the partially controlled system. The cost per gas cart unit was the same for both systems at approximately $96,000. Gas carts can range in cost from as low as $20,000 to as high as $175,000 depending on their size (Rothlisberger, 2011a), and a mid-range gas cart size was assumed for both system types in this analysis. The average capital costs for the partially controlled system are less than the cost per unit, because U.S. systems have implemented SF_6 recycling to a greater extent and fewer gas carts are needed across U.S. systems: less than one per system.
- **Annual operation and maintenance (O&M) costs.** O&M costs were estimated to be $5,000 for the uncontrolled system and $20,000 for the partially controlled system. The lower O&M costs for the uncontrolled system were driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue.** Annual revenue, which was estimated based on the reduction of SF_6 emissions multiplied by the cost per pound of SF_6 gas, was close to $68,000 for the uncontrolled system and $6,000 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system because the uncontrolled system has not implemented the option at all, while the partially controlled system has implemented the option to 85% of its potential—therefore the potential for reductions is greater. In addition, the cost of SF_6 per pound varies regionally and is relatively low in the United States (Rothlisberger, 2011a), so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 15 years.
- **Reduction Efficiency:** The reduction efficiency for SF_6 recycling is 90%.

IV.10.3.2 Leak Detection and Leak Repair (LDAR)

LDAR is a two-step process. First, a leak detection technique is used to identify gas leaks from SF_6-insulated equipment. Leak detection methods vary and can involve simple techniques such as using soap and water solutions to more sophisticated techniques such as those requiring cameras to visualize the source of SF_6 leaks by exploiting the strong infrared adsorption of SF_6 for detection. Thermal imaging cameras allow the detection of even minor leaks without the need to take equipment out of service. The abatement option analyzed in this analysis is the use of a thermal imaging camera. Identified leaks are typically repaired by applying a sealing material to the component that is leaking, although in some cases the component needs to be replaced completely. The International Council on Large Electric Systems (CIGRE), published "SF6 Tightness Guide" (Brochure No. 430) offers details on more specific methods for leak detection and tightness procedures and test methods (CIGRE, 2010).

Emissions addressed by LDAR occur when a piece of equipment periodically develops a manageable leak from a specific component such as a bushing flange gasket. Once the leak is repaired, the equipment tends to last months to years without another major leak. SF_6 emissions from periodic equipment leakage account for 10% of emissions from both uncontrolled systems (in developing countries) and partially controlled systems (in the United States) (Rothlisberger, 2011a; 2011b).

Emission reductions from LDAR were estimated to be 800 pounds for the uncontrolled system and 440 pounds for the partially controlled system. The lifetime of this abatement option is five years (Czerepuszko, 2011a). Cost and revenue estimates for LDAR are summarized below:

- **Capital costs.** The capital costs associated with purchasing thermal imaging cameras were estimated to be $95,000 for an uncontrolled abatement system and $91,000 for a partially controlled system. The cost for a single thermal imaging camera was approximately $98,000 (Czerepuszko, 2011a).
- **Annual O&M costs.** O&M costs were estimated to be $540 for the uncontrolled system and $6,300 for the partially controlled system. The lower O&M costs for the uncontrolled system were driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of SF_6 emissions multiplied by the cost per pound of SF_6 gas, was $12,600 for the uncontrolled system and $3,500 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, because the cost of SF_6 per pound varies regionally and costs significantly less in the United States (Rothlisberger, 2011a), the cost of SF_6 per pound is significantly less for the partially controlled system relative to systems in other regions, and so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is five years.
- **Reduction Efficiency:** The reduction efficiency for LDAR is 50%.

IV.10.3.3 Equipment Refurbishment

Unlike LDAR, which tends to focus on small leaks on specific components such as a bushing flange gasket, refurbishment addresses the need for a comprehensive repair from equipment that chronically leaks large amounts of SF_6 gas. Refurbishment is a process in which equipment is disassembled and rebuilt (and possibly upgraded) using remachined, cleaned, and/or new components. The option is focused mostly toward dual-pressure circuit breakers built before 1980, which hold large amounts of SF_6

and were initially built with gasket material that corroded metal within the breaker (resulting in numerous leaks over time).

Although the leaks can be temporarily repaired using the LDAR option (and often are), using LDAR over time requires high servicing costs because of the extent of the LDAR required and the amount of gas needed to replace the emitted gas. Using LDAR only for this category of equipment also increases the risk for system reliability issues. Ultimately the equipment needs to be refurbished or replaced for these issues to be solved.

Based on expert judgment, SF_6 from chronically leaking equipment accounts for 20% of emissions from uncontrolled systems (in developing countries) and 40% of emissions from partially controlled systems (in the United States).

Emission reductions from equipment refurbishment were estimated to be 600 pounds for the uncontrolled system and 670 pounds for the partially controlled system. The lifetime of this abatement option was estimated to be 20 years based on the assumption that the average lifetime of new equipment was 40 years, and the lifetime of refurbished equipment will be about half that of new equipment. Cost and revenue estimates for equipment refurbishment are summarized below:

- **Capital costs.** The capital costs associated with equipment refurbishment were estimated to be \$125,000 for an uncontrolled system and \$450,000 for a partially controlled system. The estimated cost to replace a single 1,130-pound nameplate capacity circuit breaker was estimated to be \$143,000 (developed from McCracken et al. [2000]).
- **Annual O&M costs.** It was assumed that the equipment refurbishment is conducted off-site of the system facility by the manufacturer and that there are no incremental O&M costs associated with the equipment after it has been refurbished and returned to the EPS.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of SF_6 emissions multiplied by the cost per pound of SF_6 gas, was \$9,600 for the uncontrolled system and \$5,300 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, the cost of SF_6 per pound is significantly less for the partially controlled system, so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 20 years.
- **Reduction Efficiency:** The reduction efficiency for equipment refurbishment is 95%.

IV.10.3.4 Improved SF_6 Handling

This option involves improving the procedures and techniques for handling SF_6, especially when maintenance is being performed on gas-insulated circuit breakers. Handling-related leaks can occur when (1) inappropriate fittings are used to connect transfer hoses to cylinders or equipment; (2) SF_6 is not cleared from transfer hoses before the hoses are disconnected from cylinders/equipment; (3) gas cylinders are not monitored/maintained because they have been misplaced or stored improperly; and (4) any time SF_6 is accidently vented by a technician. Improving SF_6 handling involves both training technicians to properly handle gas and purchasing adapter kits that ensure proper fittings are available for connecting hoses to all gas-insulated equipment throughout the system.

SF_6 emissions from handling-related leaks account for 40% of emissions from both uncontrolled systems (in developing countries) and partially controlled systems (in the United States) (Rothlisberger, 2011a; 2011b).

Employee training and investments in SF_6 handling technologies (such as SF_6 recovery carts) are measures that improve SF_6 handling; several technical references are available with detailed guidance on the proper techniques for recovering, disposing and other handling practices of SF_6 gas (CIGRE, 2005; IEC, 2008; IEEE, 2012). Emission reductions from improved SF_6 handling were estimated to be 5,800 pounds for the uncontrolled system and 3,200 pounds for the partially controlled system. The lifetime of this abatement option was one year, with training conducted on an annual basis (Rothlisberger, 2011a). Cost and revenue estimates for the improved SF_6 handling option are summarized below:

- **Capital costs.** The capital costs associated with improved SF_6 handling were estimated to be $13,500 for both the uncontrolled system and the partially controlled system. This capital cost consists entirely of purchasing adapter kits, which were estimated to cost $1,350 each (middle of cost range provided by Rothlisberger [2011a]).
- **Annual O&M costs.** O&M costs were estimated to be $250 for the uncontrolled system and $2,500 for the partially controlled system. The lower O&M cost for the uncontrolled system was driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of SF_6 emissions multiplied by the cost per pound of SF_6 gas, was $91,000 for the uncontrolled system and $25,000 for the partially controlled system. Annual revenue was significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, the cost of SF_6 per pound is significantly less for the partially controlled system, so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 1 year.
- **Reduction Efficiency:** The reduction efficiency for improved SF_6 handling is 90%.

IV.10.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for SF_6 emissions reduction.

IV.10.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section for two types of EPS systems, defined earlier as uncontrolled and partially controlled systems, to calculate a break-even price for the options available for each EPS system.

IV.10.4.2 Definition of EPS Model Facilities

Key Characteristics of the Residual Emissions System

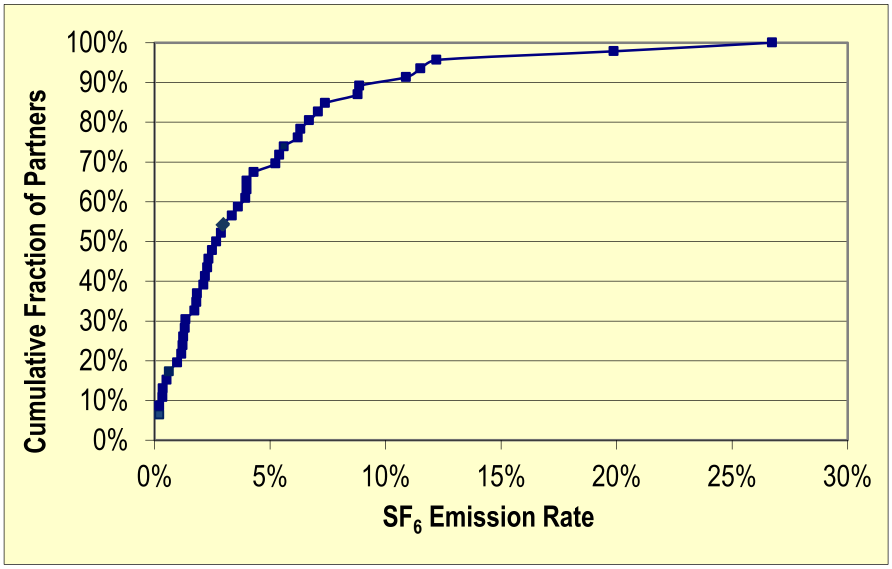
Facilities in Europe and Japan have been classified as residual emission systems. In these regions, abatement options are close to fully implemented. The vast majority of the SF_6 emissions that do occur are considered residual emissions from occurrences such as catastrophic equipment failure and accidents associated with gas handling (Rhiemeier et al., 2010). Japanese equipment designs and maintenance practices are believed to be similar to those in Europe (Yokota et al., 2005). Country-reported data as reported in UNFCCC inventory submissions for Europe and Japan show that SF_6 emissions from electric power systems have declined from 1990 through 2003. Emissions are expected to continue to decline in these regions as utilities, through government-sponsored voluntary and mandatory programs, implement reduction measures such as leak detection and repair and gas recycling practices (USEPA, 2012).

Key Characteristics of the Partially Controlled System

In the last decade, electric utilities have begun to voluntarily reduce SF$_6$ emissions by applying the abatement options included in this analysis (USEPA, 2011a). The baseline emission projections for the partially controlled system were developed under the assumption that the adoption of abatement technologies and practices in the United States will continue to grow into the future (as it has over the last decade through voluntary efforts such as USEPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems). For purposes of the engineering cost analysis, the emission rate for the partially controlled system was 8.8%, which was the average U.S. emission rate in 2009 as estimated by USEPA (2011b). The size of the partially controlled system was a typical medium-sized facility with 100,000 pounds of installed SF$_6$ nameplate capacity. The size of the system was chosen to yield realistic nominal abatement and cost values because the size of a system in the United States does not significantly influence the system's emission rate, baseline abatement levels, or other key characteristics.

Figure 10-5 presents 2010 emission rates from EPSs that participate in the USEPA voluntary Partnership. Emission rates reported through the Partnership contributed to the average U.S. emission rate of 8.8% used in this analysis (USEPA, 2011a).

Figure 10-5: Distribution of 2010 Emission Rates Reported through USEPA's Voluntary Partnership



Source: USEPA, 2011a

Key Characteristics of the Uncontrolled System

The baseline emission projections for developing countries were developed under the assumption that the application of abatement technologies does not increase in the future. For purposes of the engineering cost analysis, the assumed emission rate for the uncontrolled system was 16%, which is approximately double the U.S. emission rate. The emission rate for the developing world is very uncertain because a published emission rate based on actual measurements of emissions is not known. The 16% emission rate was developed by considering a probable emission rate for an EPS in the United States (for which emission rates are available) if that system had similar characteristics to the average system in the developing world. The size of the uncontrolled system was a typical medium-sized system with 100,000 pounds of installed SF_6 nameplate capacity. The size of the system was chosen simply to yield realistic nominal abatement and cost values because the size of a system in developing countries does not significantly influence the system's emission rate, baseline abatement levels, or other key characteristics.

Table 10-4 lists the countries or regions associated with each model facility system. The residual emissions systems include Japan and Europe, which includes a majority of European Union member countries, in additional to Norway and Switzerland. The United States and Canada represent partially controlled systems, and the rest of the world reflects uncontrolled systems.

Table 10-4: EPSs System Country Mapping

Residual Emission Systems			Partially Controlled	Uncontrolled Systems
Japan			**United States**	**Rest of World**
Europe			**Canada**	
Austria	Greece	Portugal		
Belgium	Hungary	Romania		
Bulgaria	Ireland	Slovakia		
Cyprus	Italy	Slovenia		
Czech Republic	Latvia	Spain		
Denmark	Lithuania	Sweden		
Estonia	Luxembourg	Switzerland		
Finland	Netherlands	United Kingdom		
France	Norway			
Germany	Poland			

IV.10.4.3 Parameters Used to Estimate Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each abatement measure/system type combination. Estimating this parameter requires making a number of assumptions regarding estimates of technical applicability, market penetration, and reduction efficiency. These assumptions are held constant for all model years. Table 10-5 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness.

IV.10.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits and technical lifetime as described in Section IV.10.3 to calculate the break-even price for each mitigation option at each model facility. Table 10-6 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Improved SF_6 handling is the only options with a negative break-even price, also known as a "no-regrets" option because the benefits of adopting the abatement measure outweigh the costs of implementation. The remaining three options have break-even prices greater than \$0/tCO_2e.

Table 10-5: Technical Effectiveness Summary

Abatement Option	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Developing Countries				
SF_6 Recycling	30%	100%	90%	**27%**
LDAR	10%	100%	50%	**5%**
Equipment Refurbishment	20%	20%	95%	**4%**
Improved SF_6 Handling	40%	100%	90%	**36%**
United States/Canada				
SF_6 Recycling	10%	100%	90%	**9%**
LDAR	10%	100%	50%	**5%**
Equipment Refurbishment	40%	20%	95%	**8%**
Improved SF_6 Handling	40%	100%	90%	**36%**

Table 10-6: Example Break-Even Prices for Abatement Measures in EPSs

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price[a] ($\$/tCO_2e$)
Developing Countries					
SF_6 Recycling	46,833	$2.2	−$1.3	$0.5	**$0.45**
LDAR	8,673	$4.8	−$1.4	$1.5	**$1.98**
Equipment Refurbishment	6,591	$3.7	−$1.5	$0.6	**$1.65**
Improved SF_6 Handling	62,444	$0.4	−$1.4	$0.1	**−$1.20**
United States/Canada					
SF_6 Recycling	8,618	$1.8	$1.6	$0.4	**$3.05**
LDAR	4,788	$8.4	$0.6	$2.5	**$6.45**
Equipment Refurbishment	7,278	$12.2	−$0.7	$2.1	**$9.40**
Improved SF_6 Handling	34,474	$0.7	−$0.7	$0.3	**−$0.20**

[a] Break-even prices were calculated using a tax rate of 40% and a discount rate of 10%.

IV.10.4.5 MAC Analysis Results

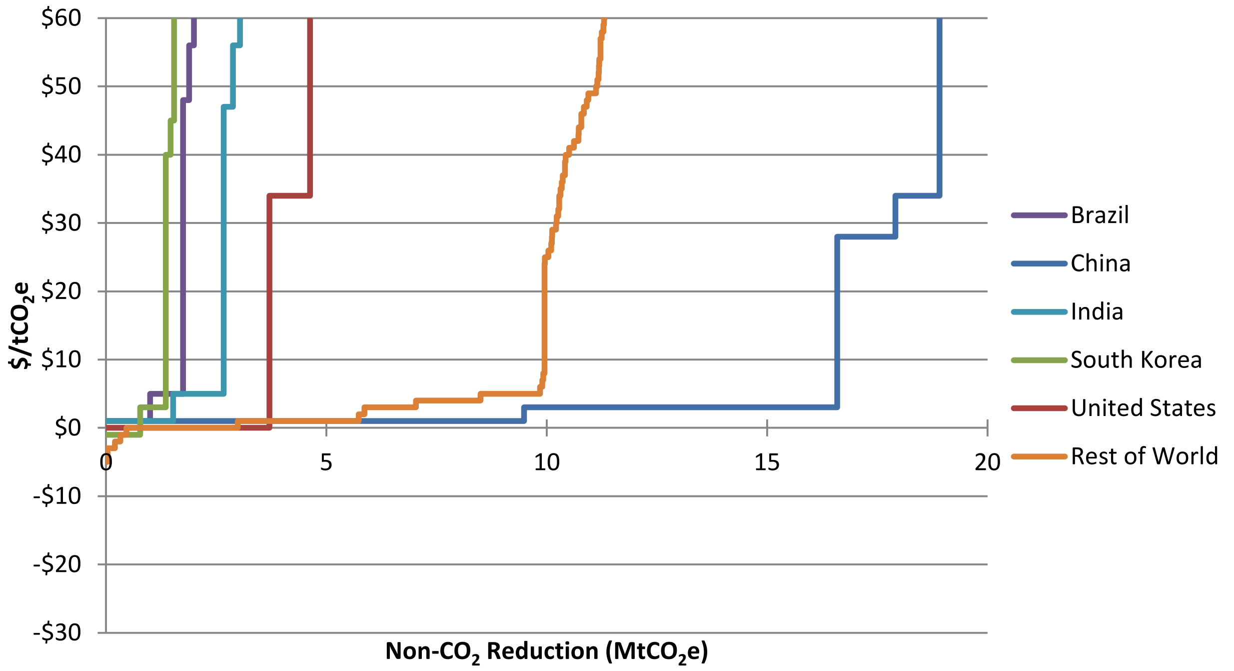
The global abatement potential for SF_6 reductions in the EPS sector is estimated to be 43 $MtCO_2e$, which is 67% of total projected emissions in 2030. Table 10-7 presents the cumulative reductions achieved at selected break-even prices. Figure 10-6 shows the MAC curve for the top five emitting countries in the EPS sector. Over 83% of the maximum abatement potential is achieved at break-even prices below $\$5/tCO_2e$ in 2030.

Table 10-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 (MtCO$_2$e)

	Break Even Price ($/tCO$_2$e)										
Country/Region	**10**	**5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
Brazil	—	—	—	1.7	1.7	1.7	1.7	1.7	1.9	2.0	2.0
China	—	—	—	16.6	16.6	16.6	16.6	17.9	18.9	18.9	18.9
India	—	—	—	2.7	2.7	2.7	2.7	2.7	2.9	3.0	3.0
South Korea	—	—	0.8	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5
United States	—	—	3.7	3.7	3.7	3.7	3.7	3.7	4.6	4.6	5.9
Rest of Regions											
Africa	—	—	0.6	1.8	1.8	1.8	1.8	2.0	2.0	2.0	2.0
Central and South America	—	—	0.4	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2
Middle East	—	0.0	0.7	1.9	2.0	2.0	2.0	2.0	2.2	2.2	2.2
Europe	—	—	0.3	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7
Eurasia	—	—	0.1	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8
Asia	—	—	0.4	3.0	3.0	3.0	3.0	3.0	3.4	3.4	3.4
North America	—	—	0.5	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0
World Total	**—**	**0.0**	**7.5**	**35.9**	**36.0**	**36.0**	**36.0**	**37.6**	**41.0**	**41.5**	**42.8**

[a] The World Total may not equal the sum of the country and region break-even prices due to small differences in rounding.

Figure 10-6: Marginal Abatement Cost Curves for Top Five and Rest of World Emitters in 2030



IV.10.5 Uncertainties and Limitations

Despite a comprehensive literature review and correspondence with some of the most knowledgeable representatives from the electric power transmission and distribution industry, considerable uncertainty is associated with some of the engineering cost data used for this analysis. Emission data account for the greatest area of uncertainty.

We are not aware of any published information on emission levels or rates in the developing world that are based on actual measurements. Also, there is very limited information on the distribution of emissions within a typical EPS because the system-level mass-balance approach (currently the standard emissions monitoring method) does not track where or how emissions occur. The lack of reliable continuous emission monitoring methods at specific points within EPSs also makes it difficult to accurately monitor the reduction efficiencies associated with specific abatement options, so the reduction efficiencies used for this analysis are based on judgments from industry experts rather than the studies involving emissions monitoring. Much less uncertainty is associated with cost data because most cost data were obtained directly from industry representatives that provide the equipment and services for abating emissions.

References

Czerepuszko, P. May 13, 2011a. Documentation of meeting between Paul Czerepuszko of FLIR Systems and Paul Stewart of ICF International.

Czerepuszko, P. May 23, 2011b. Documentation of meeting between Paul Czerepuszko of FLIR Systems and Paul Stewart of ICF International.

International Council on Large Electric Systems (CIGRE). 2005. *Guide for the Preparation of Customised "Practical SF6 Handling Instructions."* Brochure No. 276.

International Council on Large Electric Systems (CIGRE). 2010. *SF_6 Tightness Guide*; Brochure No. 430.

International Electrotechnical Commission (IEC). 2008. *High-voltage Switchgear and Controlgear – Part 303: Use and Handling of Sulphur Hexafluoride (SF6)*. IEC Technical Report 62271-303.

Institute of Electrical and Electronics Engineers (IEEE). 2012. *IEEE Guide for Sulphur Hexafluoride (SF6) Gas Handling for High-Voltage (over 1000 Vac) Equipment*. IEEE Std C37.122.3.

McCracken, G., R. Christiansen, and M. Turpin. 2000. The Environmental Benefits of Remanufacturing: Beyond SF_6 Emission Remediation. Obtained at: http://www.epa.gov/electricpower-sf6/documents/conf00_mccracken_paper.pdf.

North China Grid Company (NCGC). 2010. SF_6 Recycling Project of North China Grid—Project Design Document. North China Grid Company. CDM Project 3707. Obtained at: http://cdm.unfccc.int/Projects/Validation/DB/MPHV4MMDLVU2I0E4ZP69TWKSRAT3HB/view.html.

National Electric Power Authority (NEPA). 2005. Reducing SF_6 Emissions in High-Voltage Transmission/Distribution Systems in Nigeria—Project Design Document. National Electric Power Authority. NM0135. Obtained at: http://cdm.unfccc.int/methodologies/PAmethodologies/pnm/byref/NM0135.

Rhiemeier, J., S. Wartmann, M. Pagnotta, N. Makowska, and X. Li. 2010. Update on Global SF_6 Emissions Trends from Electrical Equipment—Edition 1.1. Ecofys Emission Scenario Initiative on Sulphur Hexafluoride for Electric Industry. Obtained at: http://www.ecofys.com/files/files/esi-sf6_finalreport_edition11_100701_v01.pdf.

Rothlisberger, L. May 5, 2011a. Documentation of meeting between Lukas Rothlisberger of DILO and Paul Stewart of ICF International.

Rothlisberger, L. June 2, 2011b. Documentation of meeting between Lukas Rothlisberger of DILO and Paul Stewart of ICF International.

Smythe, K. December 1-3, 2004. Trends in SF_6 Sales and End-Use Applications: 1961-2003. International Conference on SF_6 and the Environment: Emission Reduction Technologies, Scottsdale, AZ.

United Nations Framework Convention on Climate Change (UNFCCC). 2009. United Nations Framework Convention on Climate Change Flexible GHG Data Queries. Obtained at: http://unfccc.int/di/FlexibleQueries/Setup.do.

U.S. Bureau of Labor Statistics (BLS). 2011. "International Comparisons of Hourly Compensation Costs in Manufacturing." Press Release on December 21, 2011. Bureau of Labor Statistics, U.S. Department of Labor. USDL-11-1778. Obtained at: http://www.bls.gov/news.release/pdf/ichcc.pdf.

U.S. Energy Information Administration (EIA). 2009. International Energy Outlook 2009. Energy Information Administration, U.S. Department of Energy. Report# DOE/EIA-0484(2009). Obtained at: http://www.eia.gov/oiaf/archive/ ieo09/index.html.

U.S. Environmental Protection Agency (USEPA). (2011a). SF_6 Emission Reduction Partnership for Electric Power Systems—2010 Annual Report. U.S. Environmental Protection Agency. Obtained at: http://www.epa.gov/electricpower-sf6/documents/sf6_2010_ann_report.pdf.

U.S. Environmental Protection Agency (USEPA). (2011b). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. U.S. Environmental Protection Agency. USEPA #430-R-11-005. Obtained at: http://epa.gov/climatechange/emissions/usinventoryreport.html.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

Yokota, T., K. Yokotsu, K., Kawakita, H. Yonezawa, T. Sakai, and T. Yamagiwa. 2005. Recent Practice for Huge Reduction of SF_6 Gas Emissions from GIS&GCB in Japan. Presented at the CIGRE SC A3 & B3 Joint Colloquium in Tokyo.

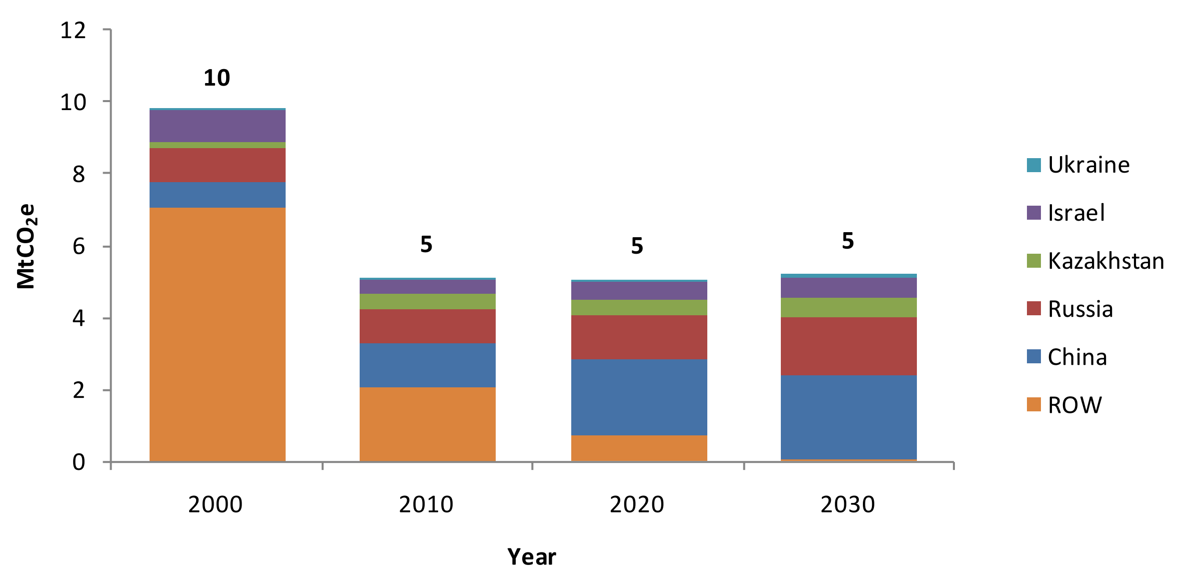
IV.11. SF_6 Emissions from Magnesium Production

IV.11.1 Sector Summary

The magnesium metal production and casting industry uses SF_6 as a cover gas to prevent the spontaneous combustion of molten magnesium in the presence of air. Fugitive SF_6 emissions occur primarily during three magnesium manufacturing processes: primary production, die-casting, and recycling-based production. Additional processes that may use SF_6 include sand and gravity casting, as well as wrought, anode, and permanent mold casting; however, these are not included in this analysis.

Between 2000 and 2010, global SF_6 emissions from magnesium manufacturing have decreased 50%, from 10 million metric tons of carbon dioxide equivalent ($MtCO_2e$) to 5 $MtCO_2e$ (USEPA, 2012). Over this time period, magnesium production has increased, but growth has been offset by major initiatives to phase out the use of SF_6 in magnesium production in numerous countries. As Figure 11-1 shows, from 2010 to 2030, emissions from magnesium production are projected to stay in the range of approximately 5 $MtCO_2e$ (USEPA, 2012).

Figure 11-1: SF_6 Emissions from Magnesium Production: 2000–2030 ($MtCO_2e$)

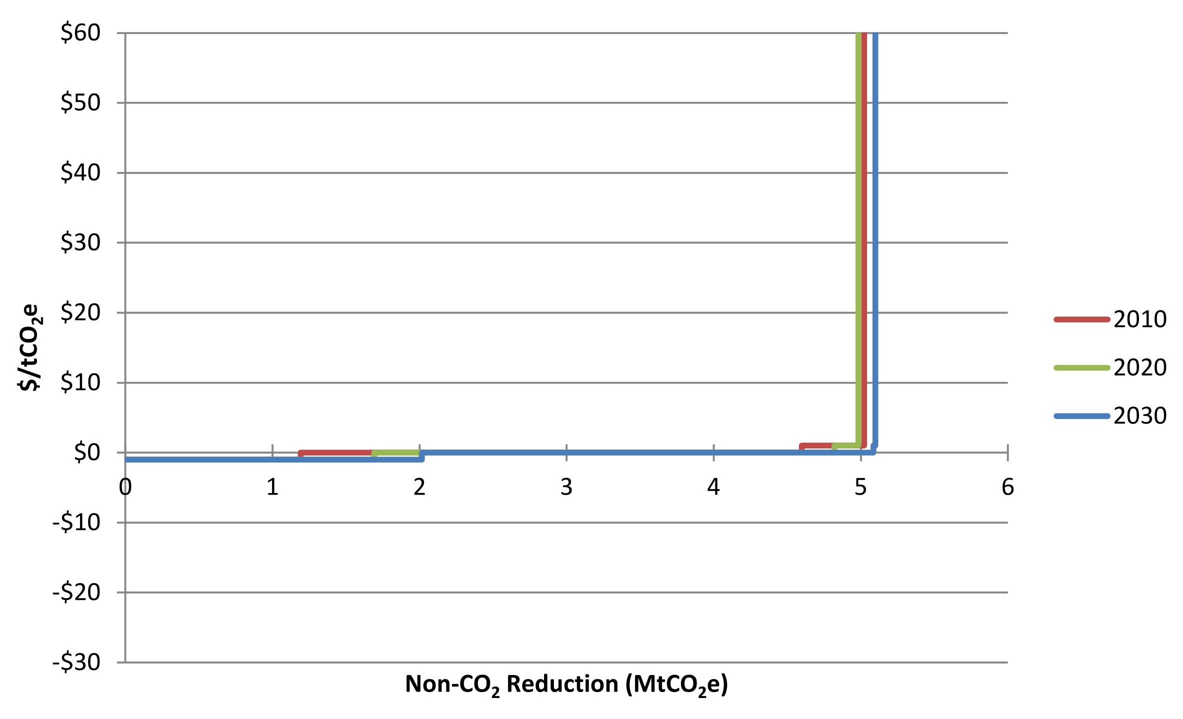


ROW = Rest of World

Source: U.S. Environmental Protection Agency (USEPA), 2012.

Global abatement potential of SF_6 in the magnesium manufacturing sector is 5 $MtCO_2e$ in 2030, which is approximately 98% of the projected emissions. Figure 11-2 presents the sector marginal abatement cost (MAC) curves for 2010, 2020, and 2030. Three potential options are available for reducing SF_6 emissions from magnesium production and processing operations. These emission abatement measures all include substituting SF_6 with an alternate cover gas: SO_2, HFC-134a, or Novec™ 612.

Figure 11-2: Global Abatement Potential in Magnesium Manufacturing: 2010, 2020, and 2030



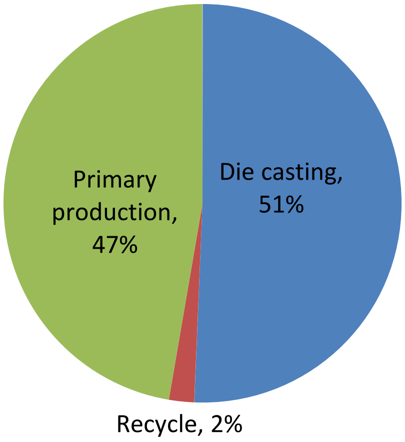
This chapter follows a structure similar to previous chapters, starting with a description of the industrial activity, facility types, and source of emissions, followed by a discussion of the projected emissions out to 2030. Section IV.11.3 characterizes the abatement measures by providing a brief description of each option and information on their costs and performance assumptions. The chapter concludes with a discussion of regional MAC results.

IV.11.2 SF_6 Emissions from Magnesium Manufacturing

Use of SF_6 as a cover gas is the only source of emissions from magnesium production. Although studies indicate some destruction of SF_6 in its use as a cover gas (Bartos et al., 2003), the analysis described here follows current Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006), which assumes that all SF_6 used is emitted to the atmosphere. This analysis uses three model facilities to define magnesium production across die casting, primary production, and reprocessing (recycle/remelt) facilities. Global SF_6 emissions from magnesium production by facility type are shown in Figure 11-3. Model facilities are based on industry data from the United States, but apply to magnesium facilities globally.

For the purpose of evaluating the cost of reducing SF_6 emissions from magnesium production, this analysis considers reduction costs for three typical magnesium production facilities—die casting, recycle/remelt, and primary production, which were generally characterized based on facility-specific case studies measuring average SF_6 consumption, production capacity, and type. We characterize these typical facilities as follows:

Figure 11-3: Global SF_6 Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



- **Die Casting Facility:** This model facility represents a medium-sized die casting facility. The facility is characterized based on real data from a case study (USEPA, 2011) where a given abatement option was implemented in 2008. The facility produces 26,014 metric tons of magnesium per year, and emits 0.17 kg of SF_6 per metric ton of magnesium produced, representing a total annual facility emission of 4,483 kg of SF_6. Production and emissions data from 2007 is used to define the pre-abatement emissions baseline (USEPA, 2011). Emissions data was reported by the facility based on its consumption of SF_6, assuming all SF_6 used is emitted to the atmosphere.
- **Recycle/Remelt Facility:** This model facility represents a medium-sized recycle facility. The facility is characterized based on real data from a case study where a given abatement option was implemented in 2008. The facility produces 18,453 metric tons of magnesium per year, and emits 1.09 kg of SF_6 per metric ton of magnesium produced, representing a total annual facility emission of 20,026 kg of SF_6. Production and emissions data from 2007 is used to define the pre-abatement emissions baseline (USEPA, 2011). Emissions data were reported by the facility based on its consumption of SF_6, assuming all SF_6 used is emitted to the atmosphere.
- **Primary Production Facility:** Assumes the same characteristics as the die casting facility.

IV.11.2.1 Activity Data or Important Sectoral or Regional Trends

The primary activity data for this sector are the quantities of magnesium produced or processed. Between 1990 and 2010, global SF_6 emissions from magnesium manufacturing have decreased 58%, from 12 $MtCO_2e$ to 5 $MtCO_2e$ (USEPA, 2012). Over this time period, magnesium production has increased, but this growth has been offset by major initiatives to phase out the use of SF_6 in magnesium production in numerous countries.

From 2010 to 2030, emissions from magnesium production are projected to stay in the range of approximately 5 $MtCO_2e$ (USEPA, 2012). Emissions from Organisation for Economic Co-operation and Development (OECD) countries decrease substantially in the short term because of facility closures in North America and SF_6 phaseout efforts (U.S. Geological Survey [USGS], 2011). As a result, the OECD share of global SF_6 emissions from magnesium manufacturing is projected to decrease from 40% in 2010 to 12% in 2030. Major SF_6 phaseout efforts are driven by the USEPA's voluntary partnership in the United States, and the regulatory directives in Japan and Europe.

SF_6 emissions from magnesium manufacturing in non-OECD Asia are projected to increase significantly between 2010 and 2030, increasing the region's global share of emissions from 20% to 44%. Emissions in the non-OECD Europe and Eurasia region experience similar growth. The overall increase in non-OECD Asia's share of global emissions results from an increase in Chinese primary magnesium production and die casting fueled by local and foreign investment. China's emissions growth is driven by their die casting operations as well as by the share of China's primary production (approximately 10%) that is assumed to use SF_6 as the cover gas mechanism. Emissions from Central and South America are driven by production in Brazil. Brazil's emissions were estimated to have declined considerably since implementation of a Clean Development Mechanism project after 2005 involving a switch to SO_2 as the cover gas (UNFCCC, 2010).

IV.11.2.2 Emission Estimates and Related Assumptions

Global emissions from the magnesium production sector were 5.13 $MtCO_2e$ in 2010, growing to 5.22 $MtCO_2e$ in 2030. Emission estimates for U.S facilities were based on magnesium production statistics and specific emissions factors for each manufacturing process using data from the USEPA SF_6 Emission Reduction Partnership (USEPA, 2011) and USGS (2011). As per IPCC 2006 guidelines, it is assumed that all SF_6 used as a cover gas is emitted. Data used in this analysis on magnesium production and cover gas use for a typical facility were taken from a case study on U.S. facilities (USEPA, 2011) and may vary for facilities in other countries. Table 11-1 presents projected emissions between 2010 and 2030 by country and region.

Table 11-1: Projected Baseline Emissions from Magnesium Production: 2010–2030 ($MtCO_2e$)

Country/Region	2010	2015	2020	2025	2030	CAGR[a] (2010 2030)
Top 5 Emitting Countries						
China	1.2	1.6	2.1	2.2	2.3	3.2%
Russia	0.9	1.1	1.2	1.4	1.6	2.6%
Kazakhstan	0.4	0.5	0.5	0.5	0.6	1.7%
Israel	0.4	0.4	0.5	0.5	0.6	1.7%
Ukraine	0.1	0.1	0.1	0.1	0.1	1.7%
Rest of Region						
Africa	—	—	—	—	—	—
Central and South America	0.1	0.0	0.0	0.0	0.0	—
Middle East	—	—	—	—	—	—
Europe	0.2	0.0	0.0	0.0	0.0	−22.2%
Eurasia	—	—	—	—	—	—
Asia	0.6	0.6	0.6	0.0	0.0	−20.8%
North America	1.3	0.4	0.2	0.1	0.1	−13.3%
World Total	**5.1**	**4.6**	**5.1**	**4.8**	**5.2**	**0.1%**

[a] CAGR = Compound Annual Growth Rate
Source: USEPA, 2012

IV.11.3 Abatement Measures and Engineering Cost Analysis

Three potential options are available for reducing SF_6 emissions from magnesium production and processing operations. These emission abatement measures all include replacing SF_6 with an alternative cover gas: SO_2, HFC-134a, or Novec™ 612. Table 11-2 presents the reduction efficiency and applicability for the three alternative cover gas options.

The remainder of this section provides an overview of each abatement option and details the cost and reduction assumptions.

Table 11-2: Magnesium Production Abatement Options

Abatement Option	Reduction Efficiency	Applicability
Alternative cover gas—Novec™ 612	100%	Die casting
		Recycle/remelt
		Primary production
Alternative cover gas—HFC-134a	95%	Die casting
		Recycle/remelt
		Primary production
Alternative cover gas—SO_2	100%	Die casting
		Recycle/remelt
		Primary production

IV.11.3.1 Replacement with Alternative Cover Gas—Sulfur Dioxide (SO_2)

Historically, SO_2 has been used as a cover gas in magnesium production and processing activities. However, because of toxicity, odor, and corrosivity concerns, SO_2 use was discontinued in most countries. Current SO_2 technology research aims to improve process feed systems and control technology, as well as to address the toxicity and odor issues with improved containment and pollution control systems (Environment Canada, 1998). The use of SO_2 has the potential to reduce SF_6 emissions by 100% because a complete replacement of the cover gas system is involved. Currently, SO_2 is being used as a cover gas; for example, it is used as a cover gas at one diecasting facility in Brazil (UNFCCC, 2010). This option is assumed to be technically applicable to all three model facilities. The maximum market penetration for this option is assumed to be 80% of the emissions of SF_6 for recycle/remelt facilities, and 10% for both die casting and primary production facilities. The lifetime of this option is assumed to be 15 years.

Facilities implementing SO_2 as an alternative cover gas incur capital costs related to the cost for new piping, pollution control equipment, and safety equipment for workers. The total capital cost was $490,781 for all three facility types. Facilities also incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. This option results in annual gas purchase costs of $16,763 each for die casting and primary production facilities and an annual gas purchase cost of $74,833 for recycle/remelt facilities. SO_2 is significantly less expensive than SF_6, and the required gas replacement ratio is 1:1, resulting in a significant net savings in material costs. Replacing SF_6 with SO_2 also results in avoided costs of $131,633 each for both die casting and primary production model facilities and $588,018 for the recycle/remelt model facility associated with the purchase of SF_6.

IV.11.3.2 Replacement with Alternative Cover Gas—HFC 134a

Research has shown that candidate fluorinated compounds such as HFC-134a can be a cover gas substitute for SF_6 (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). In addition, currently, HFC-134a is used as a cover gas at two diecasting facilities in Israel (UNFCCC, 2008a, 2008b).While fluorinated gases have an advantage over SO_2 because they have potentially fewer associated health, safety, odor, and corrosive impacts, some current fluorinated gas alternatives (including HFC-134a) still have global warming potential (GWP). However, the GWP of HFC-134a is significantly less than that of SF_6: thus, the GWP-weighted cover gas emissions could be reduced by 95%. HFC-134a is assumed to be technically applicable to all model facilities. The maximum market penetration for this option is assumed to be 45% of the emissions of SF_6 for die casting and primary production facilities, and 10% for recycle/remelt facilities. The lifetime of this option is assumed to be 15 years.

Facilities implementing HFC-134a as an alternative cover gas do not incur up-front capital costs, as use of HFC-134a is a simple drop-in option and does not require additional/new systems or training. They incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. Use of HFC-134a results in annual gas purchase costs of $32,908 each for die casting and primary production facilities and $147,005 for the recycle/remelt facility. HFC-134a is not only less expensive than SF_6, but additionally HFC-134a has a gas replacement ratio of 0.5:1, resulting in significant net savings in material costs. Replacing SF_6 with HFC-134a results in avoided costs of $131,633 each for both die casting and primary production model facilities and $588,018 for the recycle/remelt facility associated with the purchase of SF_6.

IV.11.3.3 Replacement with Alternative Cover Gas—Novec™ 612

Research has shown that candidate fluorinated compounds such as Novec™ 612 can be a cover gas substitute for SF_6 (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). Additionally, currently, Novec™612 is being used at one die casting facility in the United States. The use of Novec™ 612 as an alternative cover gas represents an advantage over SO_2 because, like other fluorinated gases, Novec™ 612 has potentially fewer associated health, safety, odor, and corrosive impacts. Novec™ 612 is a zero GWP gas and therefore has a reduction efficiency of 100% compared with SF_6. Novec™ 612 is assumed to be technically applicable to all model facilities.

Facilities implementing Novec™ 612 as an alternative cover gas incur capital costs related to the purchase of computerized mass flow control cabinets and piping material to direct the gas. The total capital cost was $245,390 for the die casting facility, $33,128 for the recycle/remelt facility, and $496,916 for the primary production facility. Facilities also incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. Use of Novec™612 results in annual gas purchase costs of $60,754 for die casting and primary production facilities and $271,393 for the recycle/remelt facility. However, because the replacement ratio of Novec™ 612 to SF_6 is 0.3:1, significantly less Novec™ 612 is required to process the same quantity of magnesium. These costs are offset by the avoided costs of purchasing SF_6, an annual cost savings of $131,633 for both die casting and primary production model facilities and $588,018 for the recycle/remelt model facility.

IV.11.3.4 Summary of Mitigation Technology Costs and Characteristics

Table 11-3 presents all of the data needed to calculate the break-even price for the options analyzed. All options have an assumed lifetime of 15 years.

Table 11-3: Engineering Cost Data on a Facility Basis

Abatement Option	Facility Type	Project Lifetime (Years)	Capital Costs (2010 USD)	Annual Savings* (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
SO_2	Die casting	15	$490,781	$131,633	$16,763	107,144
	Recycle/remelt	15	$490,781	$588,018	$74,883	478,621
	Primary production	15	$490,781	$131,633	$16,763	107,144
HFC-134a	Die casting	15	—	$131,633	$32,908	101,316
	Recycle/remelt	15	—	$588,018	$147,005	452,588
	Primary production	15	—	$131,633	$32,908	101,316
Novec™ 612	Die casting	15	$245,390	$131,633	$60,754	107,139
	Recycle/remelt	15	$33,128	$588,018	$271,393	478,601
	Primary production	15	496,916	$131,633	$60,754	107,139

* These numbers are not net annual savings.

IV.11.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for magnesium production.

IV.11.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at three magnesium production facility types to calculate a break-even price for each option at each facility (i.e., die casting, recycle/remelt, and primary production). This section presents detailed information on how each type of facility was defined in this analysis and detailed information on how costs were built out for each mitigation technology.

IV.11.4.2 Model Facilities Defined

The break-even cost analysis is conducted on three model facility types defined as follows:

- **Die casting facility**—Represents medium-sized facility currently in production in the United States where abatement option was implemented in 2008. Annual production is assumed to be 26 kilo tons. The annual SF_6 usage rate was 0.17kg/ ton produced (based on data reported by facility under USEPA SF_6 Emission Reduction Partnership). This emission factor multiplied by the annual production of magnesium yields annual facility emissions of approximately 4.4 tons of SF_6 (equal to 107,550 tCO_2e).
- **Recycle/Remelt facility**—Represents medium-sized facility currently in production in the United States where abatement option was implemented in 2008. Production data is from 2007, prior to implementation of abatement option. Annual production is assumed to be 18 kilo tons. The annual SF_6 usage rate was 1.09 kg/ ton of magnesium produced (based on data reported by facility under USEPA SF_6 Emission Reduction Partnership). This emission factor multiplied by the annual production yields annual facility emissions of approximately 20 tons of SF_6.
- **Primary production facility**—Assumes similar characteristics as the die casting model facility. Annual magnesium production is 26 kilotons and a SF_6 usage rate of 0.17 kg/ton of production. The model primary production facility annual emissions are 4.4 tons of SF_6.

IV.11.4.3 Assessment of Technical Effectiveness

For this analysis, we developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility-type combination. Table 11-4 lists the assumptions regarding technical applicability, market penetration, and technical effectiveness of each option.

Table 11-4: Technical Effectiveness Summary

Abatement Option	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Die Casting Facility				
Alternative cover gas—Novec™ 612	100%	45%	100%	**45%**
Alternative cover gas—HFC-134a	100%	45%	95%	**43%**
Alternative cover gas—SO_2	100%	10%	100%	**10%**
Recycle/Remelt Facility				
Alternative cover gas—Novec™ 612	100%	10%	100%	**10%**
Alternative cover gas—HFC-134a	100%	10%	95%	**9%**
Alternative cover gas—SO_2	100%	80%	100%	**80%**
Primary Production Facility				
Alternative cover gas—Novec™ 612	100%	45%	100%	**45%**
Alternative cover gas—HFC-134a	100%	45%	95%	**43%**
Alternative cover gas—SO_2	100%	10%	100%	**10%**

We assume that all three abatement measures are technically applicable to all facility types, hence the technical applicability factor of 100%. Market penetration rates were assumed based on expert judgment. For example, for die casting facility experts believe that a facility would adopt both Novec™612 and HFC-134a over SO_2, with an equal chance of adopting either Novec™612 or HFC-134a. The same assumptions were made for a primary production facility. For recycle/remelt facility, experts believed that there would be a preference for SO_2 over the other two alternative cover gases, with an equal chance of adopting either Novec™612 or HFC-134a. Multiplying the technical applicability, market penetration, and reduction efficiency for each alternative cover gas at each facility type produces the technical effectiveness estimates for each facility type. These assumptions are held constant for all model years.

IV.11.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.11.3 to calculate the break-even price for each mitigation option at each model facility. Table 11-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Die casting and recycle facility types have negative break-even prices for all three abatement measures. The only positive break-even price estimated was for alternate cover gas—Novec™ 612 when applied to the primary production facility due to a higher initial capital cost compared with other facility types. The remaining two abatement measures applied to the primary production facility have negative break-even prices.

IV.11.4.5 MAC Analysis Results

The global abatement potential for SF_6 reductions in the magnesium manufacturing sector is estimated to be 98% of total projected emissions in 2030. Table 11-6 presents the cumulative reductions achieved at selected break-even prices. Figure 11-4 shows the MAC curve for the top five emitting countries for this sector. Total abatement potential is achieved at break-even prices below \$5/tCO_2e in 2030.

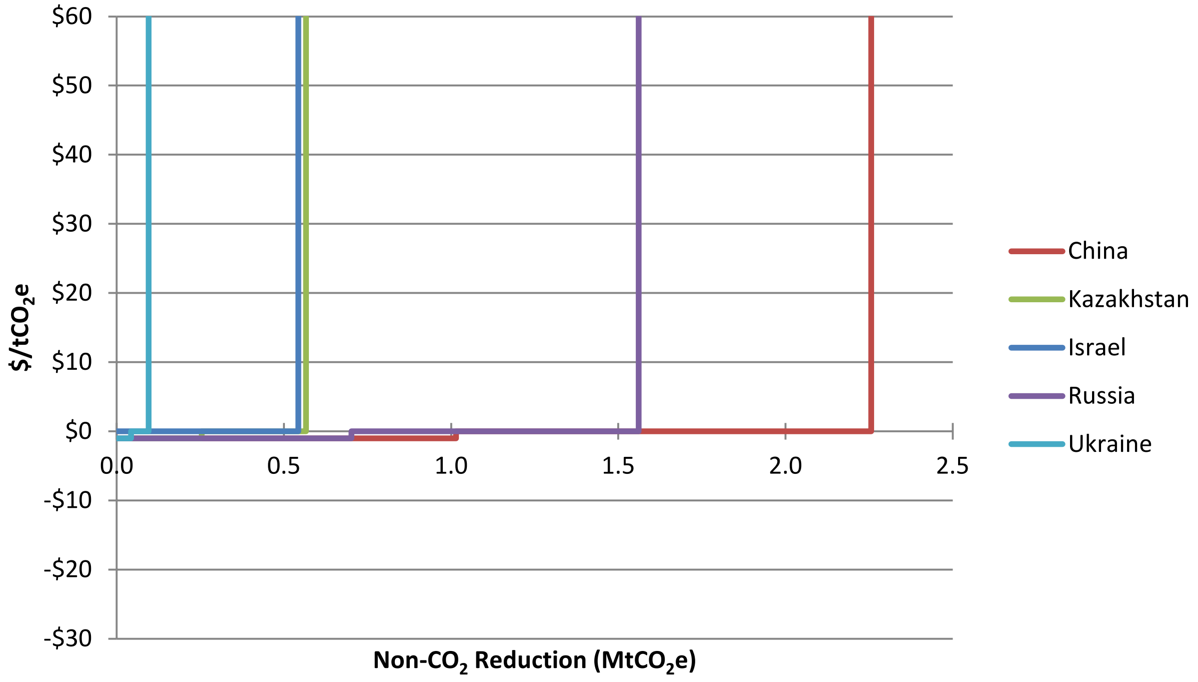
Table 11-5: Example Break-Even Prices for Abatement Measures in Magnesium Manufacturing

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break-Even Price ($\$/tCO_2e$)
Die Casting Facility					
Alternative cover gas—Novec™ 612	107,139	$0.50	−$0.66	$0.10	**−$0.26**
Alternative cover gas—HFC-134a	104,230	$0.00	−$0.95	$0.00	**−$0.95**
Alternative cover gas—SO_2	107,144	$1.00	−$1.07	$0.20	**−$0.27**
Recycle/Remelt Facility					
Alternative cover gas—Novec™ 612	478,601	$0.02	−$0.66	$0.00	**−$0.65**
Alternative cover gas—HFC-134a	465,605	$0.00	−$0.95	$0.00	**−$0.95**
Alternative cover gas—SO_2	478,621	$0.22	−$1.07	$0.05	**−$0.89**
Primary Production Facility					
Alternative cover gas—Novec™612	107,139	$1.02	−$0.66	$0.21	**$0.15**
Alternative cover gas—HFC-134a	104,230	$0.00	−$0.95	$0.00	**−$0.95**
Alternative cover gas—SO_2	107,144	$1.00	−$1.07	$0.20	**−$0.27**

Table 11-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($\$/tCO_2e$)										
Country/Region	10	5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	—	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Israel	—	—	—	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Kazakhstan	—	—	—	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Russia	—	—	—	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Ukraine	—	—	—	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rest of Region											
Africa	—	—	—	—	—	—	—	—	—	—	—
Central and South America	—	—	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	—	—	—	—	—	—	—	—	—	—	—
Europe	—	—	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eurasia	—	—	—	—	—	—	—	—	—	—	—
Asia	—	—	—	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North America	—	—	—	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
World Total	**—**	**—**	**—**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**

Figure 11-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



IV.11.5 Uncertainties and Limitations

As per IPCC guidelines (2006), this analysis assumes that all cover gas used is emitted during magnesium production. However, any SF_6 destruction that occurs during use would result in lower emission estimates than currently assumed in this analysis. In addition, this analysis uses data available from U.S. facilities that implemented the three abatement options available. Although the data are representative of abatement costs for U.S. facilities, the data may not be equally applicable to facilities in other countries. Finally, uncertainties are associated with the emission estimates, which are detailed in the Global Emissions Report.

References

Bartos, S., J. Marks, R. Kantamaneni, C. Laush. 2003. Measured SF_6 Emissions from Magnesium Die Casting Operations. Magnesium Technology 2003, Proceedings of The Minerals, Metals & Materials Society (TMS) Conference, March 2003.

Environment Canada. 1998. *Powering GHG Reductions through Technology Advancement.* Clean Technology Advancement Division, Environment Canada.

Hillis, J.E., 2002. *The International Program to Identify Alternatives to SF_6 in Magnesium Melt Protection.* Presented at the International Conference on SF_6 and the Environment: Emissions Reduction Technologies, November 21-22, San Diego, CA.

Intergovernmental Panel on Climate Change (IPCC). 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Meridian. 2011. Personal Communication between Charles Woodburn of Meridian Magnesium Products and Neha Mukhi of ICF International. May 24, 2011.

Milbrath, D. 2002. *Development of 3M Novec 612 Magnesium Protection Fluid as a Substitute for SF_6 in the Magnesium Industry*. Presented at the International Conference on SF_6 and the Environment: Emissions Reduction Technologies, November 21-22, San Diego, CA.

Ricketts, N. 2002. *Environmental Implications of Using HFC-134a as a Replacement for SF_6 in the Magnesium Industry*. Presented at the International Conference on SF_6 and the Environment: Emissions Reduction Technologies, November 21-22, San Diego, CA.

United Nations Framework Convention on Climate Change (UNFCCC). 2008a. SF_6 Switch at Ortal Diecasting 1993 Ltd. Production. United Nations Framework Convention on Climate Change. Obtained May 2010 at: http://cdm.unfccc.int/Projects/DB/TUEV-SUED1233931497.2/view.

United Nations Framework Convention on Climate Change (UNFCCC). 2008b. SF_6 Switch at Dead Sea Magnesium. United Nations Framework Convention on Climate Change. Obtained May 2010 at: http://cdm.unfccc.int/Projects/DB/TUEV-SUED1235638608.46/view.

United Nations Framework Convention on Climate Change (UNFCCC). 2010. Conversion of SF_6 to the Alternative SO_2 at RIMA Magnesium Production. United Nations Framework Convention on Climate Change. Obtained May 2010 at: http://cdm.unfccc.int/Projects/DB/TUEV-SUED1239262577.48/view.

U.S. Environmental Protection Agency (USEPA). (2012). *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA. Obtained from: http://www.epa.gov/climatechange/economics/international.html.

U.S. Environmental Protection Agency (USEPA). 2011. Case Study: U.S. Magnesium Industry Adopts New Technology for Climate Protection. Washington, DC: USEPA. In process.

U.S. Geological Survey (USGS). 2011. Minerals Yearbook 2010: Magnesium. GPO Stock #024-004-02538-7, Reston, VA.

Werner K., and D. Milbrath. 2011. Novec™ 612 as a Substitute for SF_6 in Magnesium Processing: Experience to Date in Varied Casting Operations. 3M.

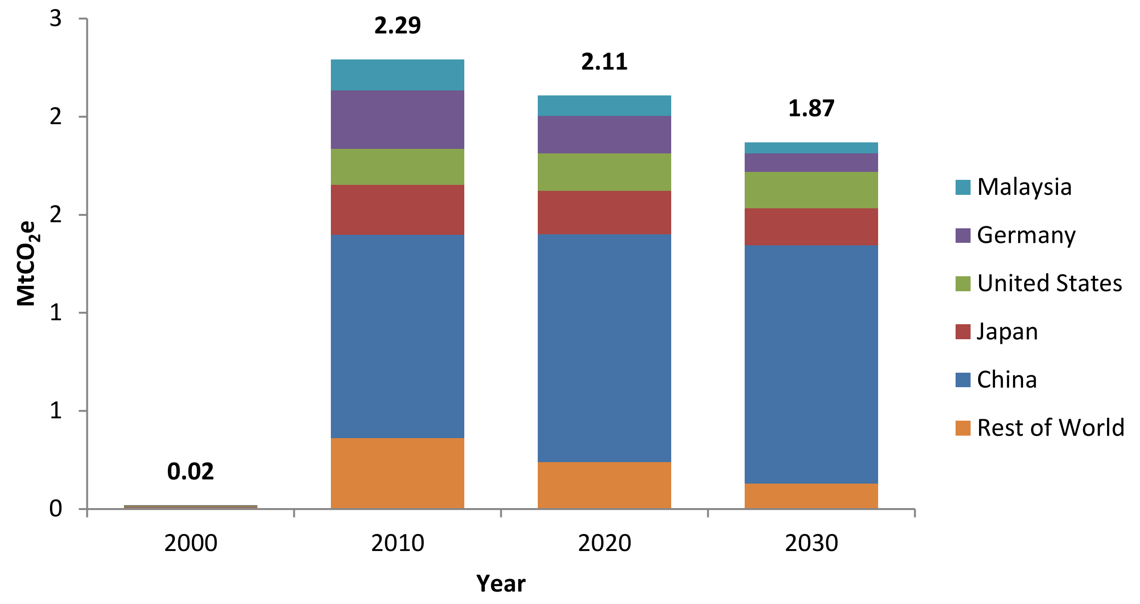
IV.12. Emissions from Photovoltaic Cell Manufacturing

IV.12.1 Sector Summary

The photovoltaic (PV) cell manufacturing process can use multiple fluorinated greenhouse gases (F-GHGs) during production, including nitrogen trifluoride (NF_3) and the perfluorocompounds (PFCs) carbon tetrafluoride (CF_4) and perfluoroethane (C_2F_6,). During the manufacture of PV cells some of the F-GHGs not used in processes are released to the atmosphere.

F-GHG emissions from PV cell manufacturing are estimated to be approximately 2.3 million metric tons of carbon dioxide equivalents ($MtCO_2e$) in 2010. As Figure 12-1 shows, by 2030, emissions from the manufacturing of PV cells are expected to decrease to 1.9 $MtCO_2e$. The baseline projections presented here are updated relative to those presented in *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 to 2030* (USEPA, 2012). The updates incorporate new market information which has resulted in significantly lower emission estimates. The decrease in emissions can be attributed to lower expected growth in production and lower fraction of production assumed to use F-GHGs. Emissions projections for this sector are particularly uncertain to due limited information on emissions rates, use of fluorinated gases, production growth rates, and policies to encourage renewable energy development.

Figure 12-1: F-GHG Emissions from PV Cell Manufacturing: 2000–2030 ($MtCO_2e$)

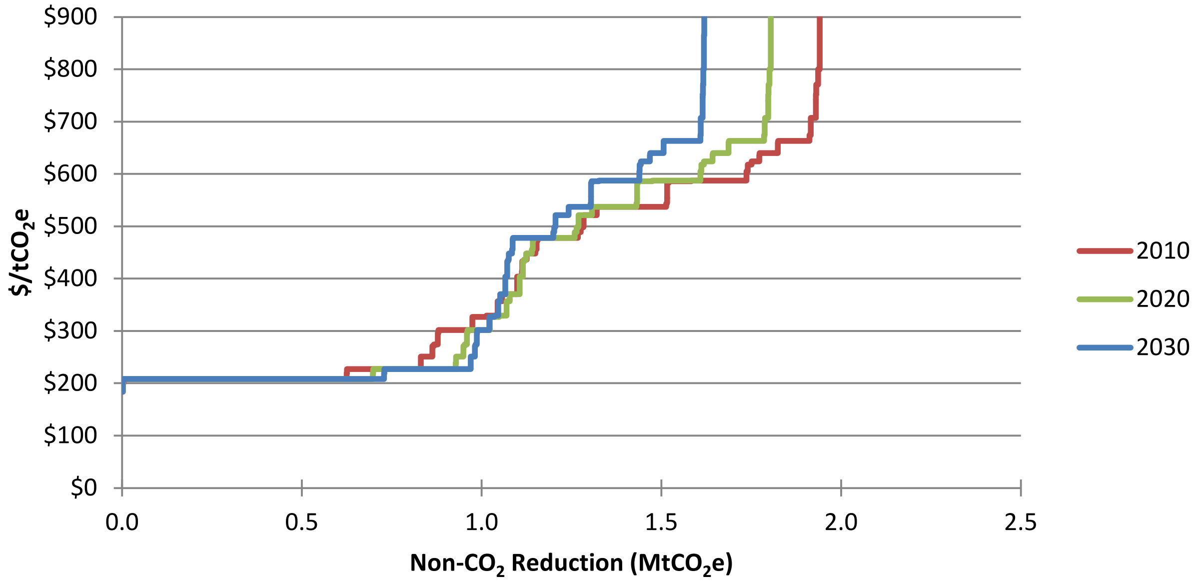


Source: Update of projections presented in USEPA, 2012.

Four mitigation technologies were considered in this analysis as options for reducing F-GHG emissions from PV manufacturing: thermal abatement systems, catalytic abatement systems, plasmas abatement systems, and the NF_3 remote chamber clean process. Due to the lack of mitigation cost information specific to PV production, data is drawn from experience reducing emissions from similar processes in semiconductor manufacturing.

The marginal abatement cost (MAC) analysis estimates a global mitigation potential of 1.7 $MtCO_2e$, based on the four abatement measures. The abatement potential represents 90% of the projected emissions in 2030. Figure 12-2 presents the global MAC curves for 2010, 2020, and 2030 for the PV manufacturing sector.

Figure 12-2: Global Abatement Potential in PV Cell Manufacturing: 2010, 2020, and 2030



High capital costs and relatively low emissions reduction amounts result in relatively high break-even prices for abatement measures in the PV manufacturing sector relative to other industrial process sectors. As a result, break-even prices in this sector are all greater than $120/$tCO_2e$.

The following sections of this chapter first describe the activities and sources of F-GHG emissions in the PV manufacturing sector and present the projected emissions for 2010 to 2030. Subsequent sections characterize the four abatement measures considered and present the engineering cost assumptions used in the MAC analysis. This is followed by a discussion of the MAC modeling assumptions that were used to estimate the global abatement potential. We conclude the chapter by presenting the MAC curves for a select number of individual countries and discuss some of the major uncertainties and limitations.

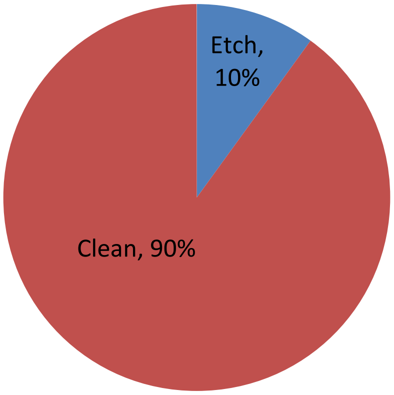
IV.12.2 Emissions from Photovoltaic Cell Manufacturing

PV manufacturing may use F-GHGs, thereby resulting in F-GHG emissions, including CF_4, C_2F_6, and NF_3, from etching and chamber cleaning processes used during the manufacture of PV cells. Etching is done on various substrates, including crystalline silicon, amorphous silicon, and other thin-films. CF_4 and C_2F_6 are used during the manufacture of some crystalline silicon (c-Si) PV cells, and NF_3 is used during the manufacture of amorphous silicon (a-Si) and tandem a-Si/nanocrystaline (nc) silicon PV cells. However, not all poly-silicon manufacturing process use F-GHGs, this was taken into consideration in the analysis. Processes for PV cells manufactured on other thin films do not require the use of GHGs; therefore, these processes were not considered in this analysis.

The emission estimates presented in Figure 12-1 represent a piece of the total life cycle emissions associated with manufacturing PV cells. One motivation of using PV cells is the production of reliable low carbon energy, so it is not only important to consider the life cycle GHG emissions but also to consider the benefits from using PV cells versus traditional fossil generated power. The European Photovoltaic Industry Association (EPIA) analyzed the life cycle of a PV cell (from material sourcing, through manufacturing, transportation, construction, operation, dismantling and to product collection and recycling into account) and estimated that "The carbon footprint of PV systems—assuming a location in southern Europe—ranges from 16 to 32 gCO_2 eq. per kWh compared to between 300 and 1000 g CO_2 eq. per kWh when produced from fossil fuels." EPIA also estimates that solar power will still have a carbon footprint of 10 to 20 times less than traditional fossil-based power with carbon capture and storage. While solar power is a good low-carbon alternative to fossil based power and over the lifetime of the cell it has climate benefits over traditional power sources, there is still potential to make it even more beneficial. According to EPIA "The carbon footprint of PV has decreased by approximately 50% in the last 10 years thanks to performance improvements, raw material savings and manufacturing process improvements" (EPIA, 2011). Implementing PFC and NF_3 mitigation strategies offers an opportunity to further decrease the carbon footprint of PV cells, particularly given the high potency of these gases.

To evaluate the cost of reducing F-GHG emissions from the manufacture of PV cells, this analysis considers the emissions and reduction costs for a typical PV manufacturing facility, characterized based on an average facility capacity and the applicability of various mitigation technologies to etch and clean emissions. The facility has an average capacity of 80 megawatts (MW) with an estimated 25 tools with 3.5 chambers. The facility uses only three F-GHGs: CF_4, C_2F_6, and NF_3.[1] Figure 12-3 shows the breakdown of etch and clean emissions for the typical facility.

Figure 12-3: Global F-GHG Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



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[1] Although these gases are used for different PV technologies, for simplicity in this analysis, one general facility producing an unidentifiable PV technology was considered.

IV.12.2.1 Activity Data and Important Sectoral/Regional Trends

Several industry trends which will influence future emissions from this sector include the rate of growth in PV panel production, the overall penetration of PV into the global energy market, and the relative proportion of various PV technologies with different rates of F-gas usage or emissions rates.

Current market trends indicate an increase and then a dip in production, and therefore, increases followed by decreases in annual emissions. Despite many slowing sectors because of the global economic slowdown, the PV sector continued to exceed expected growth rates while other sectors saw slowdowns. According to the *Global Market Outlook for Photovoltaics Until 2016*, the main reasons for the large historic and continued growth in the PV sector are: 1. "Renewable energy has continued to prove itself to be a mainstream energy source and a significant contributor to achieving energy, environmental and economic goals"; 2. "Some countries have increased their focus on renewable energy standards in the wake of the Fukushima nuclear disaster, requiring them to consider new policies that move the market in this direction"; 3. "PV modules have undergone significant price decreases…"; and 4. "In some countries, questions about the future of support-scheme levels has produced boom-and-bust cycles." Also, many countries are just starting to tap into the installed potential for PV. These factors account for the fact that there was large general growth across all regions of the world. However, in 2012, the Congressional Research Service noted that "The creation of incentives for solar installations in several countries around 2004 led many companies to enter the PV industry. According to an estimate by Photon International, more than 1,000 PV module manufacturers worldwide supplied the market in 2011. But with demand in some countries declining and prices weak, the industry appears to have entered a phase of rapid consolidation on a global basis" (CRS, 2012).

The world saw booms in PV cell manufacturing and installation. This growth however, led to an oversupply of panels starting in 2011. Balancing out supply with demand for solar panels has and resulted in factories to close, and will also result in a continued decrease in manufacturing (Forbes, 2012). There is significant uncertainty in whether production levels will remain relatively constant in the future or resume the rapid annual increases which the industry experienced prior to 2011.

The projections presented in this chapter assume that production levels will be sufficient to achieve the cumulative installed capacities from the "New Policy" Scenario of World Energy Outlook 2012, without accounting for installed capacity replacement. These assumptions result in annual production in 2030 decreased to 22.6 GW compared to 24.6 GW in 2010. While there is a growth in demand for solar energy, reflected in forecasted growth in total global installed solar capacity from about 38 gigawatts (GW) in 2010 to 491 GW in 2030 (IEA, 2012), this is expected to be met through already existing uninstalled stock of solar panels and future annual production. Figure 12-1 presents the business as usual emissions from 2000 to 2030 for the five largest emitting countries and the rest of world (ROW). Uncertainty regarding future policies, panel prices, and PV technology improvement result in particularly uncertain projections of future production and associated emissions.

IV.12.2.2 Emissions Estimates and Related Assumptions

Emissions resulting from PV manufacturing processes were estimated using projected PV cumulative installed capacities from the New Policy Scenario of World Energy Outlook, 2012; capacity and efficiency data from the DisplaySearch PV Database; an assumed solar constant of 1,000 watts per meter squared; Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors for PV manufacturing; and an NF_3 emission factor from Fthenakis et al. (2010) and an emission factor developed using sensitive process information. There is little to no variation in manufacturing processes and practices or in emissions trends on a regional basis.

F-GHG emissions from PV manufacturing are estimated to be approximately 2.29 $MtCO_2e$ in 2010. By 2030, emissions from manufacturing PV cells are expected to decrease to 1.87 $MtCO_2e$. This decrease can be attributed to the decrease in the annual PV production for 2030 compared to 2010. The annual production in 2030 is expected to decrease to 22.6 GW compared to 24.6 GW in 2010.

In December of 2012 EPA published the *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990–2030*. The baseline emission estimates presented in this analysis have been revised, and the revised estimates are used for the MAC analysis presented in this report. Like the previous estimates, since little literature is available describing the mitigation activities in the PV cell manufacturing sector, and unlike the semiconductor and FPD manufacturing sectors, the PV manufacturing sector has not set a voluntary reduction goal, the revised estimates do not include assumptions about the use of mitigation technologies for crystalline silicon type manufacturing. However, unlike the previous estimates, the baseline now assumes that half of the production process for amorphous silicon (a-Si) use abatement based on new literature published (Fthenakis et al., 2010). The baseline also assumes that half of the production process for crystalline silicon (c-Si) technology uses and emits CF_4 and C_2F_6 during manufacturing, as not all PV processes use F-GHGs.

The projected revised emissions are estimated based on annual PV production, differentiated by type of technology, country, and the emission factors for respective types. However, now the future annual PV production is estimated from the projected cumulative installed capacity obtained from World Energy Outlook, New Policy Scenario (IEA, 2012) as opposed to assumed growth rates. The total annual PV production is then differentiated into various types by dividing the total according technology proportions: 77% crystalline Silicon (c-Si), 12% amorphous Silicon (a-Si) and the rest Cadmium Telluride, Copper Indium Gallium Selenide and other categories, which are from the DisplaySearch database (DisplaySearch, 2009). Similarly, the capacity is apportioned by country based on the DisplaySearch database (DisplaySearch, 2009). Like the previous baseline methodology, PV production capacity for each country for historic years was extracted from DisplaySearch database (DisplaySearch, 2009). The area of cell produced is estimated based on the cell efficiency, using new data obtained from IEA Solar Photovoltaic Roadmap (IEA, 2010), and an assumed solar constant of 1000 W/m^2.

The NF_3 emission factor for a-Si has been updated in the revised baseline estimation methodology. For the a-Si technology, it was assumed that all facilities use NF_3 and out of those, 50% of the facilities have abatement devices installed. The emission factor for abated facilities was derived from data presented in literature looking at lifecycle NF_3 emissions of PV cells (Fthenakis et al., 2010). The emission factor for unabated facilities was developed using sensitive process information. Lastly, the revised baseline assumes that only 50% of c-Si technology is assumed to use and emit F-GHGs during manufacturing and none of the other technologies are assumed to use and emit F-GHGs.

IV.12.3 Abatement Measures and Engineering Cost Analysis

Four mitigation technology options were identified for the PV manufacturing sector: thermal abatement, catalytic abatement, plasma abatement, and NF_3 remote chamber clean.

- **Thermal abatement**: These point-of-use abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through abatement systems with catalysts (e.g., CuO, ZnO, Al_2O_3) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma in a point-of-use abatement system is used to react (destroy or remove) F-GHGs from the process effluent stream.

Table 12-1: Projected Baseline Emissions from PV Cell Manufacturing: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR[a] (2010 2030)
Top 5 Emitting Countries						
China	1.0	1.2	1.2	1.1	1.2	0.8%
Japan	0.3	0.3	0.2	0.2	0.2	−1.5%
United States	0.2	0.2	0.2	0.2	0.2	0.1%
Germany	0.3	0.3	0.2	0.1	0.1	−5.6%
Malaysia	0.2	0.1	0.1	0.1	0.1	−5.0%
Rest of Region						
Africa	—	—	—	—	—	—
Central and South America	—	—	—	—	—	—
Middle East	0.0	0.0	0.0	0.0	0.0	−5.0%
Europe	0.1	0.1	0.1	0.1	0.1	−5.0%
Eurasia	0.0	0.0	0.0	0.0	0.0	−5.0%
Asia	0.2	0.2	0.1	0.1	0.1	−5.0%
North America	—	—	—	—	—	—
World Total	**2.3**	**2.4**	**2.1**	**1.9**	**1.9**	**−1.0%**

[a] CAGR= Compound Annual Growth Rate

Source: Updated from projections presented in USEPA, 2012

- **NF_3 remote chamber clean**: Highly ionized NF_3 is used to clean chemical vapor deposition chambers. This process is highly efficient (~98%), resulting in lower emissions on a mass and CO_2 basis than traditional in-situ chamber clean processes with utilization efficiencies around 20% to 50% (IPCC, 2006).

These technologies reduce emissions from either etch or chamber clean processes, or in some cases both. Table 12-2 presents the applicability and the reduction efficiency of each abatement measure. The next sections describe each of these mitigation options and additional detail is provided in Appendix M.

Table 12-2: PV Cell Manufacturing Abatement Options

Abatement Option	Applicable 3s)	Reduction Efficiency	Information Source
Thermal abatement	Etch and clean	95%	Fthenakis (2001), Beu (2005), and USEPA (2009)
Catalytic abatement	Etch and clean	99%	Fthenakis (2001), Brown et al. (2012)
Plasma abatement	Etch	97%	Fthenakis (2001), Hattori et al. (2006)
NF_3 remote chamber clean	Clean	95%	Beu (2005)

IV.12.3.1 Thermal Abatement

Thermal abatement systems can be used to abate F-GHG emissions from both etching and chamber-cleaning processes. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in some facilities. In addition, these systems require large amounts of cooling water, and the use of the systems result in regulated NO_x emissions.

The total facility capital cost for installing thermal abatement systems is estimated to be $5.7 million. This estimate includes costs for the systems, the necessary ducting, water recirculation and hook up, and natural gas costs (Fthenakis, 2001; Burton, 2003). The annual operating cost is estimated to be $328,860 at the facility level. No annual cost savings are associated with using this technology

IV.12.3.2 Catalytic Abatement

A catalytic abatement system uses a catalyst to destroy or remove F-GHG emissions from the effluents of both plasma etching and chemical vapor deposition (CVD) chamber-cleaning processes. This type of abatement is applicable at most facilities, but again there may be some space constraints as mentioned for thermal abatement systems. Additionally, because these systems are based on destruction via catalyst, they must be process/stream specific to achieve the 99% emission reductions quoted in the literature and used in this analysis (Fthenakis, 2001; Burton, 2003).

Because catalytic destruction systems operate at relatively low temperatures, their use results in little or no NO_x emissions, and the required amounts of water are low as well. Because of the high cost of catalyst replacement, these systems are the least widely used type of abatement (expert judgment).

The capital cost associated with the purchase and installation of the abatement systems is estimated to be $6.9 million per fab (i.e., facility). To use catalytic abatement systems, facilities must factor in the annual cost of resources such as water, waste chemicals, electricity, and catalyst replacements. To cover these operating expenses, a facility manufacturing PV cells is estimated to incur an annual cost of $455,280. As with other abatement technologies considered in this sector, the use of catalytic abatement systems will not result in annual cost savings.

IV.12.3.3 Plasma Abatement

These systems are applicable to etch processes in most facilities, with some physical space limitations. (These systems though are relatively smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen (H_2), oxygen (O_2), water (H_2O), or methane (CH_4)) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no GWP. After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of PFC molecules (Burton, 2003).

The capital cost for plasma abatement systems is estimated to be $1.8 million per facility (Burton, 2003), which covers the purchase and installation of plasma systems. Plasma abatement systems require an annual operation cost of $1,190 per chamber, which includes general maintenance and use of the systems. Total annual facility costs are $51,850 based on an assumed four chambers per tool and 25 tools per facility. The use of plasma abatement systems will not result in annual cost savings.

IV.12.3.4 NF_3 Remote Chamber Clean

NF_3 remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high (~98%) utilization rate of NF_3 (IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (The stated utilization is based on utilizations for semiconductor manufacturing; as a result of large gas flows in PV manufacturing, the actual utilization may be lower.) NF_3 remote clean systems dissociate NF_3 using argon gas and converting the source gas to active F-atoms in the plasma upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine (F_2), and other gases, most of which are removed by facility acid scrubber systems.

It is assumed that PV facilities are not "NF_3 ready"; in other words, these facilities do not have the current infrastructure to handle the direct installation of NF_3 remote systems because this is a relatively new technology. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hook ups and necessary hardware such as manifolds and values. The facility cost is estimated to be $9.2 million. The annual facility cost for NF_3 remote clean is estimated to be $3.4 million (Burton, 2003). These costs are associated with the purchase of larger volumes of gas (NF_3 versus traditional chamber clean gases), general maintenance, and F_2 scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

IV.12.3.5 Summary of Mitigation Technology Costs and Characteristics

Table 12-3 summarizes the information used to estimate the break-even prices in the MAC analysis.

Table 12-3: Engineering Cost Data on a Facility Basis

Abatement Option	Project Lifetime (Years)	Capital Costs (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCO_2e)
Thermal abatement	7	$5,701,971	$0	$328,862	13,625
Catalytic abatement	7	$6,906,594	$0	$455,277	14,199
Plasma abatement	7	$1,814,664	$0	$51,848	1,398
NF_3 remote clean	25	$9,200,867	$0	$3,374,861	14,427

IV.12.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the PV manufacturing sector.

IV.12.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at two hypothetical facilities to calculate a break-even price for each abatement measure. This section presents how we defined the model facility used in this analysis and the technical effectiveness assumptions used to estimate the incremental reductions for each measure. This section also provides an example of how the break-even prices were calculated for each option.

IV.12.4.2 Definition of Model Facility

The manufacture of PV uses F-GHGs depending on the particular substrate and process used in the production. Substrates used in the industry include crystalline silicon, amorphous silicon, and other thin films. F-GHGs are used during the manufacture of crystalline silicon (c-Si) PV cells, amorphous silicon (a-Si), and tandem a-Si/nanocrystaline (nc) silicon PV cells. Other thin film PV technologies do not require the use of F-GHGs. As with the other electronics manufacturing sectors, emissions in this sector result from two main types of manufacturing processes: etching substrates and cleaning CVD chambers. Manufacturing processes and uses of GHGs across the industry are generally similar; therefore, only one type of model facility was considered for this analysis.

- **Model:** The model facility is a facility that represents a PV manufacturing facility of average manufacturing capacity (DisplaySearch, 2009) of 80 MW with an estimated 25 tools with 3.5 chambers. The facility uses only three F-GHGs: CF_4, C_2F_6, and NF_3.[2] The emissions breakdown for a PV manufacturing facility is estimated to be 10% etch emissions and 90% clean emissions.

The model facility emission breakdown is essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process.

IV.12.4.3 Assessment of Technical Effectiveness

Similar to the methods employed for analyzing abatement in the semiconductor manufacturing sector, this analysis developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process combination. Estimating this parameter required making a number of assumptions regarding the distribution of emissions by manufacturing process (etch and clean), in addition to process-specific estimates of technical applicability and market penetration. These assumptions are held constant for all model years. Table 12-4 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

Table 12-4: Technical Effectiveness Summary

	Etch (10%)		Clean (90%)			
Abatement Measure	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Thermal abatement	85%	65%	85%	20%	95%	**20%**
Catalytic abatement	85%	10%	85%	10%	99%	**8%**
Plasma abatement	85%	25%	0%	0%	97%	**2%**
NF_3 remote clean	0%	0%	100%	70%	95%	**60%**

The technical effectiveness is the weighted average of the abatement measures using the emissions attributed to each process (i.e., 10% etching, and 90% cleaning) as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency for each abatement measure.

The technical effectiveness estimates are then multiplied by the share of total emissions to estimate the abatement potential achievable under each abatement measure.

IV.12.4.4 Estimating the Break-Even Price of Abatement Measures

The MAC model uses the estimated abatement project costs and benefits as described in Section 12.3 to calculate the break-even price for each abatement measure. Table 12-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

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[2] Although these gases are used for different PV technologies, for simplicity in this analysis, one general facility producing an unidentifiable PV technology was considered.

Table 12-5: Example Break-Even Prices for Abatement Measures in PV Cell Manufacturing

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break Even Price[a] ($\$/tCO_2e$)
Thermal abatement	13,625	$143	$24	$40	$128
Catalytic abatement	14,199	$167	$32	$46	$152
Plasma abatement	1,398	$444	$37	$124	$358
NF_3 remote clean	14,427	$117	$234	$17	$334

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

As Table 12-5 shows, the high capital intensity of the abatement measures coupled with no annual benefits results in break-even prices that are all well above $100/$tCO_2e$. These significantly higher break-even prices suggest that achieving emission reductions in the PV manufacturing sector will require additional incentives or regulations to control F-GHG emissions.

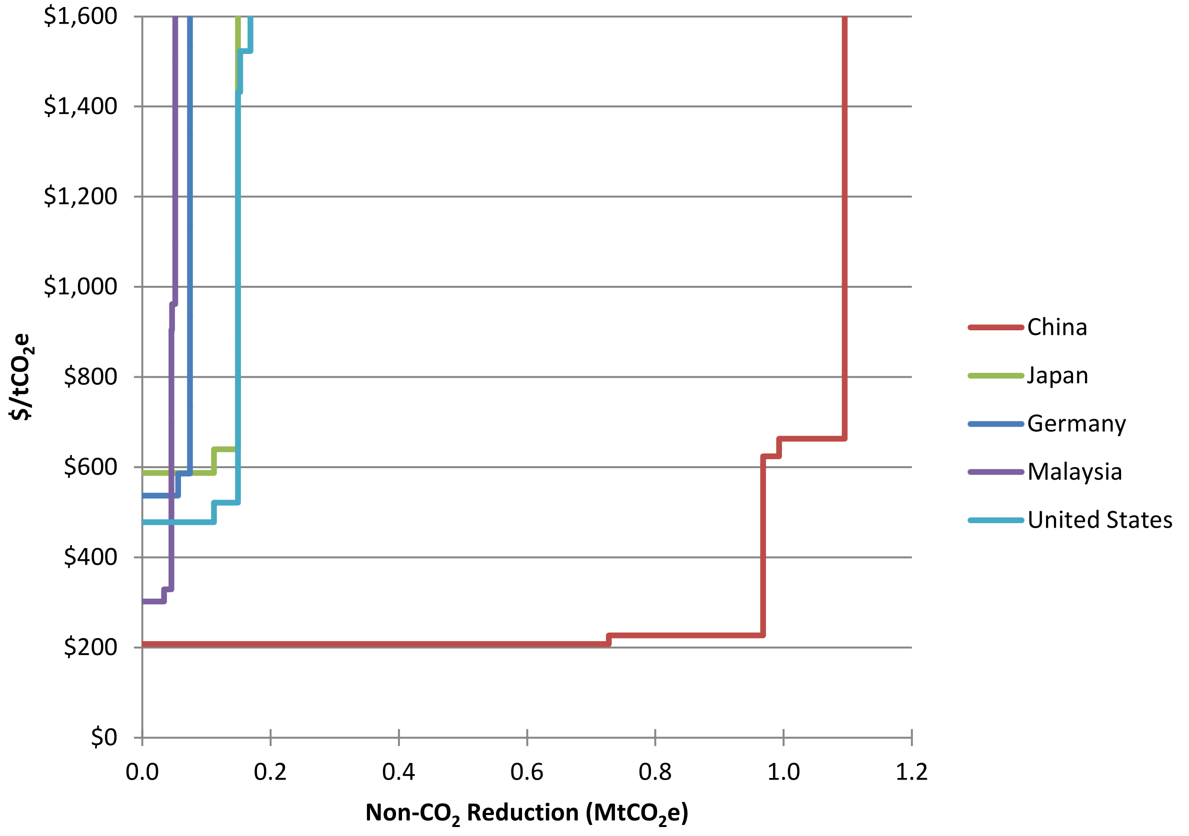
IV.12.4.5 MAC Analysis Results

The global abatement potential for F-GHG reductions in the PV manufacturing sector is estimated to be 1.7 $MtCO_2e$, or 90% of total projected emissions in 2030. Table 12-6 presents the cumulative reductions achieved at selected break-even prices for the top five emitting countries and the grouping of countries that make up the rest of each region. Figure 12-4 shows the MAC curves for the top five emitting countries and the rest of world for this sector.

Table 12-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break Even Price ($\$/tCO_2e$)										
Country/Region	−10	−5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	—	—	—	—	—	—	—	—	—	—	**1.1**
Germany	—	—	—	—	—	—	—	—	—	—	**0.1**
Japan	—	—	—	—	—	—	—	—	—	—	**0.2**
Malaysia	—	—	—	—	—	—	—	—	—	—	**0.1**
United States	—	—	—	—	—	—	—	—	—	—	**0.2**
Rest of Region											
Africa	—	—	—	—	—	—	—	—	—	—	**0.0**
Central and South America	—	—	—	—	—	—	—	—	—	—	**—**
Middle East	—	—	—	—	—	—	—	—	—	—	**—**
Europe	—	—	—	—	—	—	—	—	—	—	**0.0**
Eurasia	—	—	—	—	—	—	—	—	—	—	**0.0**
Asia	—	—	—	—	—	—	—	—	—	—	**0.1**
North America	—	—	—	—	—	—	—	—	—	—	**—**
World Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.7**

Figure 12-4: Marginal Abatement Cost Curves for Top Five Emitters and Rest of World in 2030



As the results show, the abatement potential in the PV manufacturing sector can be significant. Unfortunately, these reductions in the absence of additional regulatory or market incentives would only be achievable at significantly high break-even prices (>$200/tCO$_2$e).

IV.12.5 Uncertainties and Limitations

The PV industry is a relatively new manufacturing sector, with high levels of growth to meet continually growing demands for renewable energy. There is no comprehensive published information on the extent abatement systems are really in use in the industry. Assumed abatement system reduction efficiencies are really only achievable if the systems are properly operated and maintained, which may not always be the case (USEPA, 2008a and 2008b). Also, abatement system reduction efficiencies may vary by gas (e.g., CF_4 is harder to abate than other F-GHGs because of its thermo-stability). Additionally, there are not known voluntary reduction initiatives for the PV sector. Because of this the model facility is uncontrolled, information about the use of abatement in baseline emissions is highly uncertain.

Other reasons for uncertainties inherent to the baseline emission estimates include assumptions about the portion of the PV manufacturing industry that uses F-GHGs, and the unpredictability in the growth of the solar PV production capacity. The activity data used, the cumulative solar PV capacity, is modeled with its own set of assumptions from the IEA and is framed by the fast-growing renewable energy sector.

As this is the foundation of future baseline emission estimates, it gives rise to uncertainties. Furthermore, market dynamics will also contribute to the fluctuations with respect to facilities' utilization rates as well as fractions of PV cells started and inventoried, all of which are assumed constant for purposes of developing baseline emissions. Another limitation is that the baseline emission estimates do not take into account the retiring of PV cells. It is assumes that any new manufacturing is done to meet the increase in installed capacity and not to replace any replacement of capacity The emission estimates are hence conservative as inclusion of this assumption would lead to slightly higher emissions for each year. The use of Tier 1 emission factors to estimate emissions also gives rise uncertainty as it is the "least accurate estimation method" (IPCC, 2006). The Tier 1 method gives an aggregate emission estimate for all of the F-GHG using processes simultaneously, which introduces a higher level of uncertainty as the utilization rates of gases differ between etch and chamber cleaning processes.

Lastly, due to the similarities between this sector and the semiconductor manufacturing sector, the mitigation technologies considered for PV were those used in the semiconductor sector.

References

Applied Materials. 1999. "Catalytic Abatement of PFC Emissions." Presented at Semicon Southwest 99: Partnership for PFC Emissions Reductions, Austin, TX, October 18, 1999.

Beu, L. 2005. "Reduction of Perfluorocarbon (PFC) Emissions: 2005 State-of-the-Technology Report." TT#0510469A-ENG. International SEMATECH Manufacturing Initiative (ISMI), Albany, New York. December 2005. Obtained at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/final_tt_report.pdf.

Brown et al., 2012. "Catalytic technology for PFC emissions control." Solid State Technology. Obtained at: http://www.electroiq.com/content/eiq-2/en/articles/sst/print/volume-44/issue-7/features/emissions-control/catalytic-technology-for-pfc-emissions-control.html. Accessed August 2012.

Burton, S. 2003. Personal communication with Brown of Motorola (2002) supplemented by personal communication with Von Gompel of BOC Edwards (2003), research of DuPont's Zyron Web site (2003), and personal communication with Air Liquide regarding thermal destruction, NF_3 remote clean, and capture membrane unit costs.

CRS, 2012. "U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support." Congressional Research Service. 7-5700. R42509. June 2012. Available at: http://www.fas.org/sgp/crs/misc/R42509.pdf.

DisplaySearch. 2009. DisplaySearch Q4'09 Quarterly PV Cell Capacity Database & Trends Report. DisplaySearch, LLC, Santa Clara, California, 2009.

EPIA, 2011. "EPIA Working Group Fact Sheet: Sustainability of Photovoltaic Systems, The Carbon Footprint." European Photovoltaic Industry Association. March 2011. Available at: http://www.epia.org/publications/factsheets.html.

Forbes, 2012. "Report: Solar Panel Supply Will Far Exceed Demand Beyond 2012". Forbes. Obtained at: http://www.forbes.com/sites/uciliawang/2012/06/27/report-solar-panel-production-will-far-exceed-demand-beyond-2012/.

Fthenakis, V. December 2001. *Options for Abating Greenhouse Gases from Exhaust Streams*. Brookhaven National Laboratory, Upton, New York, 2001. Obtained at: http://www.bnl.gov/isd/documents/23784.pdf.

Fthenakis, V, Clark. D. O., Moalem, M., and Chandler, P., "Life-Cycle Nitrogen Trifluoride Emissions from Photovoltaics." Environ. Sci. Technol. 2010, vol 44, pp. 8750-8757.

Hattori et al., 2006. "Application of Atmospheric Plasma Abatement System for Exhausted Gas from MEMS Etching Process." Presetned at the Institute of Electrical and Electronics Engineers International Symposium on Semiconductor Manufacturing 2006, Tokyo, Japan, September 25-27, 2006 .

International Energy Agency (IEA). 2010. Technology Roadmap: Solar photovoltaic energy – Foldout. Available online at: http://www.iea.org/publications/freepublications/publication/name,28528,en.html.

International Energy Agency (IEA). 2012. World Energy Outlook 2012 Available for purchase at: http://www.worldenergyoutlook.org/publications/weo-2012/.

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme (Volume 3, Chapter 6: Electronics Industry Emissions), The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

U.S. Environmental Protection Agency (USEPA). (2008a). Developing a Reliable Fluorinated Greenhouse Gas (F-GHG) Destruction or Removal Efficiency (DRE) Measurement Method for Electronics Manufacturing: A Cooperative Evaluation with NEC Electronics, Inc. (EPA 430-R-10-005). Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC. Available at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/nec_report.pdf.

U.S. Environmental Protection Agency (USEPA). (2008b). Developing a Reliable Fluorinated Greenhouse Gas (F-GHG) Destruction or Removal Efficiency (DRE) Measurement Method for Electronics Manufacturing: A Cooperative Evaluation with Qimonda (EPA 430-R-08-017). Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC. Available at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/qimonda_report.pdf.

U.S. Environmental Protection Agency (USEPA). 2009. *Developing a Reliable Fluorinated Greenhouse Gas (F-GHG) Destruction or Removal Efficiency (DRE) Measurement Method for Electronics Manufacturing: A Cooperative Evaluation with IBM*. (EPA 430-R-10-004). Washington, DC: Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency. Obtained at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/ibm_report.pdf.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990–2030.* Washington, DC:USEPA, OAR, Climate Change Division. EPA 430-R-12-006. Obtained at: http://www.epa.gov/climatechange/Downloads/EPAactivities/EPA_Global_NonCO2_Projections_Dec2012.pdf.

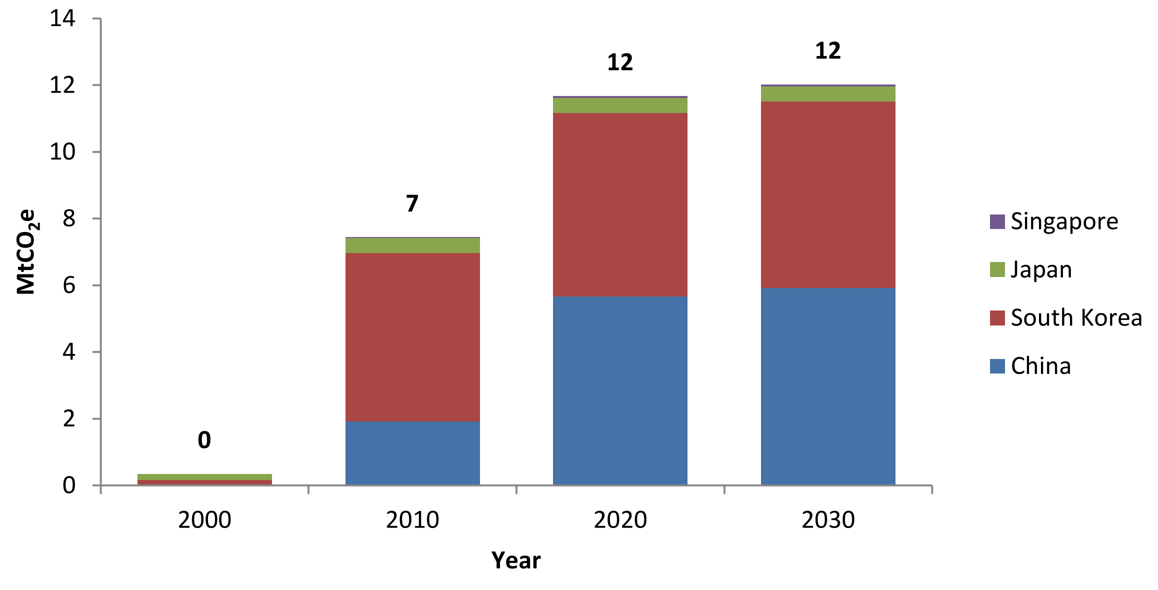
IV.13. PFC Emissions from Flat Panel Display Manufacturing

IV.13.1 Sector Summary

Flat panel display (FPD) manufacturing processes generate fluorinated greenhouse gas (F-GHG) emissions including sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and carbon tetrafluoride (CF_4), which are used in etching and chamber-cleaning processes commonly used in electronics manufacturing.

Global annual F-GHG emissions from FPD manufacturing are estimated to be approximately seven and a half million metric tons of carbon dioxide equivalents ($MtCO_2e$) in 2010, projected to grow to 12 $MtCO_2e$ by 2030.[1] Figure 13-1 shows the F-GHG emission projections by country from 2000 to 2030. The growth in emissions is primarily driven by projected growth in manufacturing capacity in China. The baseline projections presented here are updated relative to those presented in *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 to 2030* (USEPA, 2012). The updated projections include lower expected production levels of Liquid Crystal Displays and increased mitigation, resulting in significantly lower projected emissions. Emissions projections for this sector are particularly uncertain due to limited information on emissions rates and reduction efficiencies, variable industry production growth rates, and rapidly evolving FPD technologies.

Figure 13-1: F-GHG Emissions from FPD Manufacturing: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012

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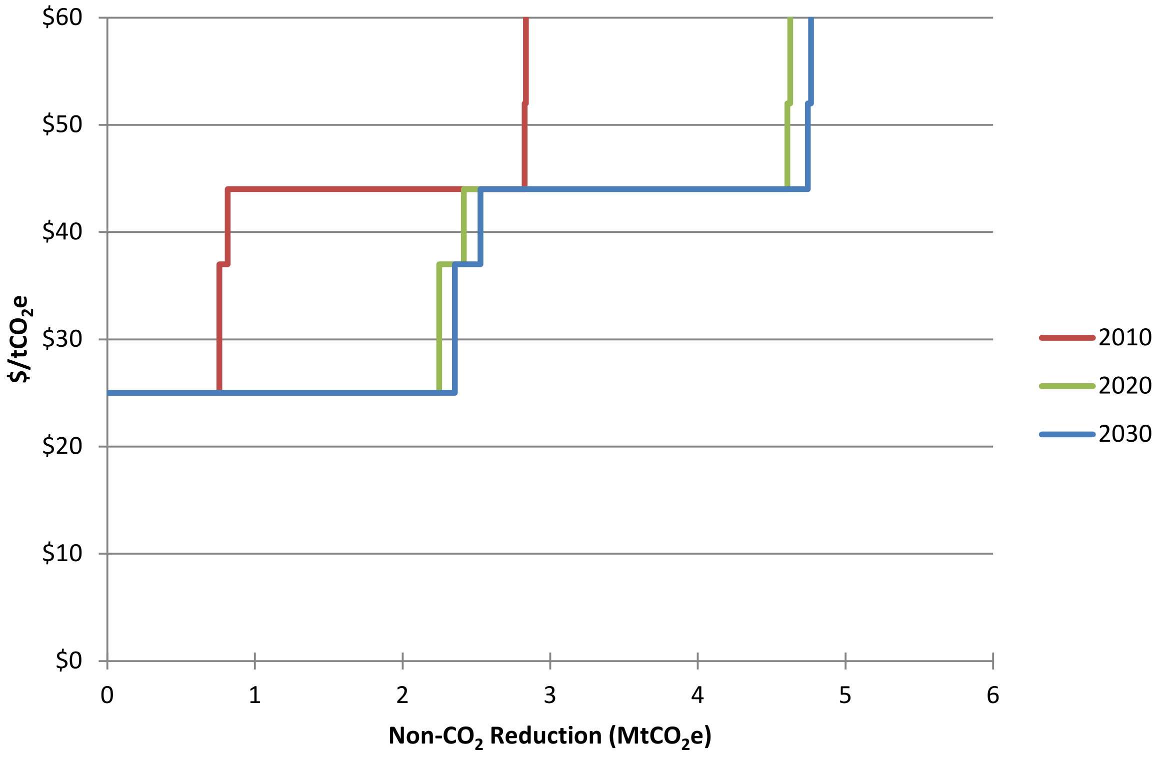
[1] The term flat panel display encompasses many technologies, such as liquid crystal displays, low temperature polysilicon (LTPS) or transparent amorphous oxide semiconductor (TAOS), and active matrix light emitting diodes (AMOLED). This analysis focuses on liquid crystal displays and does not include newer technologies such as AMOLEDs.

Six mitigation technology options were examined for this sector: central abatement, thermal abatement, catalytic abatement, plasma abatement, NF_3 remote chamber clean, and gas replacement.

Global abatement of F-GHG emissions in FPD manufacturing is estimated to be 9.3 $MtCO_2e$ in 2020 and 9.6 $MtCO_2e$ in 2030. The emissions reductions equate to 80% of the projected baseline emissions in each year. While all abatement options identified for this sector reduce emissions significantly, none has the ability to reduce or replace 100% of emissions from FPD manufacturing. Figure 13-2 presents the global MAC curves for 2010, 2020, and 2030 for the FPD manufacturing sector.

Figure 13-2: Global Abatement Potential in FPD Manufacturing: 2010, 2020, and 2030



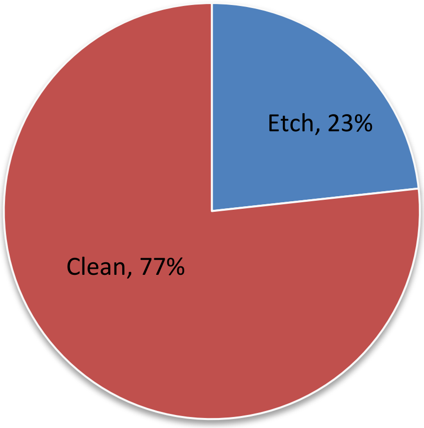
The following sections of this chapter first describe the activities and sources of F-GHG emissions in the FPD manufacturing sector and present the projected emissions for 2010 to 2030. Subsequent sections characterize the six abatement measures considered and present the engineering costs assumptions used in the MAC analysis. This is followed by a discussion of the MAC modeling assumptions used to estimate the global abatement potential. We conclude the chapter by presenting the MAC curves for each emitting country and briefly discuss some of the major uncertainties and limitations to our analysis.

IV.13.2 Emissions from Flat Panel Display Manufacturing

In FPD manufacturing, high global warming potential (GWP) greenhouse gases are used for chemical vapor deposition (CVD) cleaning processes and plasma dry etching during the manufacture of arrays of thin-film transistors on glass substrates, which switch pixels of liquid crystal displays and organic light-emitting diode displays.

To evaluate the cost of reducing F-GHG emissions from FPD manufacturing, this analysis considers the emissions and reduction costs for a typical FPD manufacturing facility (manufacturing processes and uses of GHGs across the industry are generally similar), characterized based on an average gas consumption, an assumed 25 tools per facility with approximately 3.5 chambers each, and the average emissions of F-GHGs for etch and clean processes. Figure 13-3 shows the breakdown of etch and clean emissions for the typical facility.

Figure 13-3: Global F-GHG Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



IV.13.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

FPD facility-level emissions were modeled using estimated gas consumption data based on World LCD Industry Cooperation Committee (WLICC) reported data and Intergovernmental Panel on Climate Change (IPCC) Tier 2b emission factors. Because the WLICC does not fully represent all world manufacturing capacity, global emissions were estimated using estimated global capacity, in terms of area of substrate produced, from the DisplaySearch Equipment Database and IPCC Tier 1 emission factors for FPD manufacturing as opposed to using WLICC gas consumption information.

Global emission estimates take into account the WLICC goal, which was agreed to by all three member associations. The goal is to meet and maintain an aggregate 2010 F-GHG emission target of 10% of projected business-as-usual 2010 emissions, or 3.01 $MtCO_2e$ (expressed in the goal as 0.82 million tons of carbon equivalent). (This emission reduction goal was met in 2010; hence, mitigation technologies and strategies were assumed to have penetrated the market to a certain extent already in WLICC Partner countries Japan, Taiwan, and Korea.) The WLICC member associations are estimated to have 96% of the world’s FPD manufacturing capacity in 2010. It is assumed, therefore, that there has already been some level of mitigation technology penetration to meet the stated goal in this sector in the baseline projections. Current market trends indicate major growth for capacity in this sector shifting to China, and without a reduction goal or mitigation measures, FPD emissions in China will drastically increase.

IV.13.2.2 Emissions Estimates and Related Assumptions

The large majority of FPD manufacturing is in Asia, and production capacity continues to grow in that region. As shown in Table 13-1, from 2010 to 2030, emissions from global FPD manufacturing are expected to grow by a factor of 54 times, from 3 $MtCO_2e$ in 2010 to 162 $MtCO_2e$ in 2030. Much of this growth occurs between 2015 and 2030. This increase is expected to be attributed to growth in production and emissions in China for two reasons: (1) an expected increase in China's domestic demand for FPDs, and much of this demand will be met through domestic production (DisplaySearch, 2010); and (2) China's share of world emissions is projected to steeply increase partly because emissions for the WLICC member countries are assumed to meet and maintain the reduction goal of 3.01 $MtCO_2e$.

Table 13-1: Projected Baseline Emissions from FPD Manufacturing: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR[a] (2010–2030)
China	1.9	3.8	5.7	5.8	5.9	5.8%
South Korea	5.1	5.4	5.5	5.6	5.6	0.5%
Japan	0.4	0.4	0.4	0.5	0.5	0.2%
Singapore	0.0	0.0	0.0	0.1	0.1	4.4%
World Total	**7.4**	**9.5**	**11.7**	**11.9**	**12.0**	**2.4%**

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

IV.13.3 Abatement Measures and Engineering Cost Analysis

Six mitigation technology options were identified for the FPD manufacturing sector: central abatement, thermal abatement, catalytic abatement, plasma abatement, NF_3 remote chamber clean, and gas replacement.

- **Central abatement**: These are large-scale abatement systems that are generally located on the roof of facilities and are applicable to etch emissions (SF_6).
- **Thermal abatement**: These point-of-use (POU) abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through POU abatement systems with catalysts (e.g., CuO, ZnO, Al_2O_3) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma in a POU abatement system is used to react (destroy or remove) F-GHGs from the process effluent stream.
- **NF_3 remote chamber clean**: Highly ionized NF_3 is used to clean chemical vapor deposition chambers. This process is highly efficient (using ~98% of the gas in a process) resulting in lower emissions on a mass and CO_2 basis than traditional in-situ chamber clean processes which uses approximately 20% to 50% of the gas in a process (IPCC, 2006).
- **Gas replacement**: Higher GWP gases are replaced with lower GWP gases.

Table 13-2 presents the reduction efficiency and the applicability of each mitigation technology to emissions from a type of process (etch and/or clean). The next sections describe each of these mitigation options in more detail.

Table 13-2: FPD Manufacturing Abatement Options

Abatement Option	Applicable Process Emissions Type(s)	Reduction Efficiency	Information Source
Central abatement	Etch	77%	CDM project #3333
Thermal abatement	Etch and clean	95%	Fthenakis (2001), Beu (2005), and USEPA (2009)
Catalytic abatement	Etch and clean	99%	Fthenakis (2001), Brown et al. (2012)
Plasma abatement	Etch	97%	Fthenakis (2001), Hattori et al. (2006)
NF_3 remote chamber clean	Clean	95%	Beu (2005)
Gas replacement	Clean	77%	CDM methods NM0289, NM303, NM0317, NM0335

IV.13.3.1 Central Abatement

Central abatement systems (CAS) have begun to be designed and used to handle the generally high gas (SF_6) flows used in FPD manufacturing because of the large size of the substrate being etched. A CAS is a large-scale thermal oxidation abatement system that is located on the roof of FPD facilities, so there are little expected space limitations for this technology. This technology has recently started to come online and is only applicable to etch emissions. Two CDM projects (one from LG and one from Samsung) in Korea have used this technology (CDM Project #3440 and CDM project #3333). Its use is, however, limited throughout the rest of the industry because it is expensive and relatively new.

The capital cost for a CAS is $4.5 million. The annual operation and maintenance (O&M) cost, which include items such as utilities and parts, is estimated to be $2.5 million for a facility. No revenues are generated from using a CAS.

IV.13.3.2 Thermal Abatement

Thermal abatement systems can be used to abate emissions from both etching and CVD chamber-cleaning processes. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in some facilities. In addition, these systems require large amounts of cooling water, and the use of the systems results in regulated NO_x emissions.

The total facility capital cost for installing thermal abatement systems is estimated to be $5.7 million. This estimate includes costs for the systems, the necessary ducting, water recirculation and hook up, and natural gas costs (Fthenakis, 2001; Burton, 2003). The annual operating cost is estimated to be $328,860 at the facility level. No annual savings are associated with using this technology.

IV.13.3.3 Catalytic Abatement

A catalytic abatement system is used to abate emissions from both etching and CVD chamber-cleaning processes. This type of abatement is applicable at most facilities, but again there may be some space constraints, as also discussed for thermal abatement systems, limiting the use of these systems in the market. Another limitation to their use is high catalyst replacement costs.

The capital cost associated with purchasing and installing the abatement systems is estimated to be $6.9 million per facility. To use catalytic abatement systems, facilities must factor in the annual cost of resources such as water, waste chemicals, electricity, and catalyst replacements. To cover these operating expenses, a facility manufacturing FPDs is estimated to incur an annual cost of $455,280. As with other abatement technologies considered in this sector, the use of thermal abatement systems will not result in annual savings.

IV.13.3.4 Plasma Abatement

Plasma abatement systems are assumed to be applicable to etch processes in most facilities, with some physical space limitations. (These systems, however, are relatively smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen (H_2), oxygen (O_2), water (H_2O), or methane (CH_4)) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no global warming potential (GWP). After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of F-GHG molecules (Motorola, 1998).

The capital cost for plasma abatement systems is estimated to be $1.8 million per facility (Fthenakis, 2001; Burton, 2003), which covers the purchase and installation of plasma systems. Plasma abatement systems require an annual operation cost of $1,190 per chamber, which includes general maintenance and use of the systems. The total annual facility cost is $51,850 based on an assumed number of tools per facility and chambers per tool. The use of plasma abatement systems will not result in annual cost savings.

IV.13.3.5 NF_3 Remote Chamber Clean

NF_3 remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high utilization rate of NF_3 (~98%; IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (Note: The stated utilization is based on utilizations for semiconductor manufacturing; as a result of large gas flows in FPD manufacturing the actual utilization may be lower.) NF_3 remote clean systems dissociate NF_3 using argon gas, converting the source gas to active F-atoms in the plasma, upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine (F_2), and other gases, most of which are removed by facility acid scrubber systems. The use of NF_3 remote clean systems is much more prevalent in new facilities because the technology was not available when many old facilities were constructed.

It is assumed that FPD facilities are not “NF_3 ready”; in other words, these facilities do not have the current infrastructure to handle the direct installation of NF_3 remote systems because this is a relatively new technology. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hook ups and necessary hardware such as manifolds and values. The facility cost is estimated to be $9.2 million. The annual facility cost for NF_3 remote clean is estimated to be $3.3 million (Burton, 2003). This cost is associated with the purchase of larger volumes of gas (NF_3 versus traditional chamber clean gases), general maintenance, and F_2 scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

IV.13.3.6 Gas Replacement

Gas replacement can be used to mitigate emissions from the traditional CVD chamber-cleaning process. Gas replacement can be applied in most facilities and has already been used throughout the industry in many instances. For this strategy, a lower GWP gas replaces a higher GWP gas. The most common replacement is using NF_3 to replace SF_6.

Facilities replacing SF_6 with NF_3 incur an estimated capital cost of $1.2 million for items such as gas hook ups and implementation. Annual savings for this option result from the lower cost of the replacement gas and were estimated to be $34,400, based on the incremental cost of the gases and the average amount of gas consumed per facility. Gas replacement has no operational costs.

IV.13.3.7 Summary of Mitigation Technology Costs and Characteristics

Table 13-3 summarizes the information used to estimate the break-even prices discussed in the following section.

Table 13-3: Engineering Cost Data on a Facility Basis

Abatement Option	Project Lifetime (Years)	Capital Costs (2010 USD)	Annual Revenue (2010 USD)	Annual O&M Costs (2010 USD)	Abatement Amount (tCOe)
Central abatement	15	$4,487,400	$0	$2,547,000	13,889
Thermal abatement	7	$5,701,971	$0	$328,862	62,587
Catalytic abatement	7	$6,906,594	$0	$455,277	65,222
Plasma abatement	7	$1,814,664	$0	$51,847	14,941
NF_3 remote clean	21	$9,200,867	$0	$3,374,861	56,496
Gas replacement	21	$1,180,000	$34,400	$0	22,797

IV.13.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the FPD manufacturing sector.

IV.13.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section at the model FPD manufacturing facility to calculate a break-even price for each abatement measure. This section presents how we defined the model facility used in this analysis and the technical effectiveness assumptions used to estimate the incremental reductions for each measure. This section also provides an example of how the break-even prices were calculated for each option.

IV.13.4.2 Facility Definition

The typical facility considered in this analysis represents an average-sized FPD facility, with an estimated 25 tools and 3.5 chambers per tool. Based on WLICC-reported emissions data, the facility is assumed have an emissions breakdown of 23% etch emissions and 77% chamber clean emissions, which assumes a certain level of abatement is used. The facility emission breakdown is essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process (see Table 13-2 above).

IV.13.4.3 Estimating the Technical Effectiveness Parameter

Similar to the methods employed for analyzing abatement in the semiconductor and photovoltaics manufacturing sectors, this analysis developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process combination. Estimating this parameter requires assumptions regarding the distribution of emissions by manufacturing process (etch and clean), in addition to process-specific assumptions on technical applicability and market penetration. These assumptions are held constant for all model years in the MAC analysis. Table 13-4 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

Table 13-4: Technical Effectiveness Summary

	Etch (23%)		Clean (77%)			
Abatement Measure	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Central abatement	100%	40%	0%	n/a	77%	**7%**
Thermal abatement	85%	30%	85%	55%	95%	**40%**
Catalytic abatement	85%	10%	85%	15%	99%	**12%**
Plasma abatement	85%	20%	0%	n/a	97%	**4%**
NF_3 remote clean	0%	n/a	100%	20%	95%	**15%**
Gas replacement	0%	n/a	50%	10%	77%	**3%**

The technical effectiveness is a weighted average of the abatement measure's emissions reductions when applied to each applicable process(es). The share of total emissions attributed to each process (i.e., 23% etching and 77% cleaning) is the weight which is multiplied by the product of the technical applicability, market penetration, and reduction efficiency for each abatement measure. The technical effectiveness estimates are then multiplied by the facility annual emissions to estimate the abatement potential achievable through each of the six abatement measures. Summing the technical effectiveness across the six abatement measures yields the maximum level of emissions reductions that is technically achievable.

IV.13.4.4 Estimating Break-Even Prices

The MAC model uses the estimated abatement project costs and benefits as described in Section 6.3 to calculate the break-even price for each abatement measure. Table 13-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

Table 13-5: Example Break-Even Prices for Abatement Measures in FPD Manufacturing

Abatement Option	Reduced Emissions (tCO_2e)	Annualized Capital Costs ($\$/tCO_2e$)	Net Annual Cost ($\$/tCO_2e$)	Tax Benefit of Depreciation ($\$/tCO_2e$)	Break-Even Price ($\$/tCO_2e$)
Central Abatement System	13,889	$71	$183	$14	$240
Thermal abatement	62,587	$31	$5	$9	$28
Catalytic abatement	65,222	$36	$7	$10	$33
Plasma abatement	14,941	$42	$7	$12	$37
NF3 remote clean	56,496	$31	$60	$5	$86
Gas replacement	22,797	$10	$0	$2	$8

As Table 13-5 shows, having no annual benefits and high initial capital costs results in relatively higher break-even prices. Break-even prices range between \$8 and \$240/tCO_2e based on the initial cost assumptions (unadjusted for country-specific prices). Gas replacement is the cheapest of the six options with a break-even price of \$8/tCO_2e. The CAS is the most expensive at \$240/tCO_2e. These costs are relatively high compared to some other sectors examined in this report, however they can be better understood in perspective of the high costs associated with this manufacturing industry. For example in 2004, Samsung and Sony invested more than $3 billion in capital costs for two new FPD production lines (Ramstad, 2011).

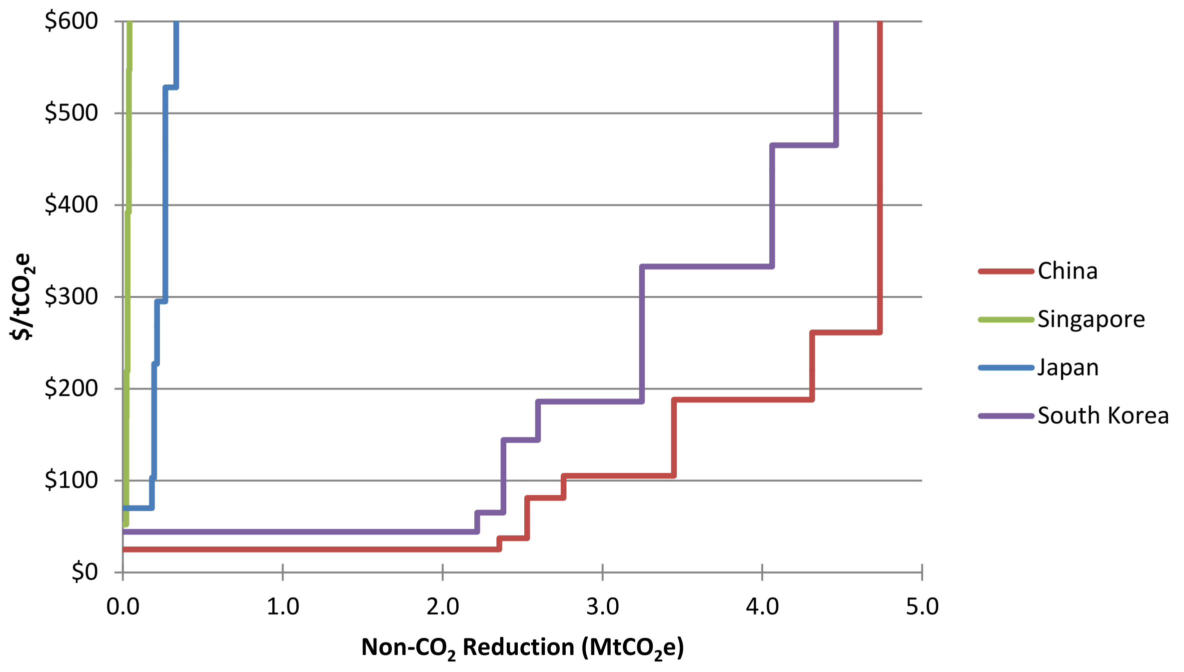
IV.13.4.5 MAC Analysis Results

The global abatement potential for F-GHG emissions reductions in the FPD manufacturing sector is estimated to be 9.6 $MtCO_2e$, or 80% of total projected emissions in 2030. Table 13-6 presents the cumulative reductions achieved at selected break-even prices for China, Japan, Singapore, and South Korea. These are the only four countries with projected emissions in 2030 in the FPD manufacturing sector. Figure 13-4 presents the resulting MAC curves for each country in 2030.

Table 13-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

	Break-Even Price ($/$tCO_2e$)										
Country	**−10**	**−5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
China	—	—	—	—	—	—	—	2.4	2.5	2.8	4.7
Japan	—	—	—	—	—	—	—	—	—	0.2	0.4
Singapore	—	—	—	—	—	—	—	—	—	0.0	0.0
South Korea	—	—	—	—	—	—	—	—	2.2	2.4	4.5
World Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.4**	**4.7**	**5.3**	**9.6**

Figure 13-4: Marginal Abatement Cost Curves by Emitting County in 2030



As the results show, the abatement potential in the FPD manufacturing sector can be significant (80% of sectoral emissions). Over 2.4 $MtCO_2e$ of F-GHG emissions could be reduced in China at a carbon price of ~$25/$tCO_2e$; these reductions alone represent 20% of global emissions in 2030.

IV.13.5 Uncertainties and Limitations

Because of the similarities between this sector and the semiconductor manufacturing sector, most mitigation technologies (and hence cost estimates) are assumed to be the same as for the semiconductor manufacturing sector (with the exception of the CAS technology). We made this assumption because of the limited amount of public information on the extent to which various types of mitigation technologies are being used in this sector.

References

Applied Materials. 1999. *Catalytic Abatement of PFC Emissions*. Presented at Semicon Southwest 99: Partnership for PFC Emissions Reductions, October 18, 1999, Austin, TX.

Bartos, S. 2010. *Draft: A Review of WLICC's Progress Toward Reducing Potent GHG Emissions from the Manufacture of Liquid Crystal Displays*. Washington DC, U.S. Environmental Protection Agency.

Beu, L. December 2005. *Reduction of Perfluorocarbon (PFC) Emissions: 2005 State-of-the-Technology Report*, TT#0510469A-ENG, International SEMATECH Manufacturing Initiative (ISMI).

Brown et. al., 2012. "Catalytic technology for PFC emissions control." Solid State Technology. Obtained at: http://www.electroiq.com/content/eiq-2/en/articles/sst/print/volume-44/issue-7/features/emissions-control/catalytic-technology-for-pfc-emissions-control.html. Accessed August 2012.

Burton, S. 2003. Personal communication with Brown of Motorola (2002) supplemented by personal communication with Von Gompel of BOC Edwards (2003), research of DuPont's Zyron Web site (2003), and personal communication with Air Liquide regarding thermal destruction, NF_3 Remote Clean, and Capture Membrane unit costs.

CDM Project #3440 and CDM project #3333. Project data available at: http://cdm.unfccc.int/Registry/index.html

DisplaySearch. 2010. *DisplaySearch Q4'09 Quarterly FPD Supply/Demand and Capital Spending Report*. DisplaySearch, LLC, Santa Clara, California, 2010.

Fthenakis, V. December 2001. *Options for Abating Greenhouse Gases from Exhaust Streams*. Brookhaven National Laboratory, Upton, New York, 2001. Obtained at: http://www.bnl.gov/isd/documents/23784.pdf.

Hattori et al., 2006. "Application of Atmospheric Plasma Abatement System for Exhausted Gas from MEMS Etching Process." Presetned at the Institute of Electrical and Electronics Engineers International Symposium on Semiconductor Manufacturing 2006, Tokyo, Japan, September 25-27, 2006 .

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme* (Volume 3, Chapter 6: Electronics Industry Emissions), The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

Motorola. October 18, 1998. "Long-term Evaluation of Litmus "Blue" Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement." Presented at Semicon Southwest 99: A Partnership for PFC Emissions Reductions, Austin, TX.

Prather, M., and J. Hsu. June 2008. "NF_3, the Greenhouse Gas Missing from Kyoto." *Geophysical Research Letters* 35.

Ramstad, E. December, 2011. "Samsung Electronics Ends LCD Venture With Sony." *Wall Street Journal US. Edition.* Published on December 27, 2011.

Rothlisberger, L. May 5, 2011. Documentation of meeting between Lukas Rothlisberger of DILO and Paul Stewart of ICF International.

U.S. Environmental Protection Agency (USEPA). 2009. *Developing a Reliable Fluorinated Greenhouse Gas (F-GHG) Destruction or Removal Efficiency (DRE) Measurement Method for Electronics Manufacturing: A Cooperative Evaluation with IBM* (EPA 430-R-10-004), Office of Air and Radiation Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC. Obtained at: http://www.epa.gov/highgwp/semiconductor-pfc/documents/ibm_report.pdf.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

V. Agriculture Sector

V.1. Non-Rice Croplands

V.1.1 Sector Summary

Land management in croplands influences soil N_2O emissions, CH_4 fluxes, and soil organic carbon (C) stocks (and associated CO_2 fluxes to the atmosphere). Soil N_2O emissions are influenced by human activity, including synthetic nitrogen fertilization practices, application of organic fertilizers such as manure, drainage of organic soils, cultivation of N-fixing crops, and enhancement of N mineralization in soils through practices such as cultivation/management of native grasslands and forests (Mosier et al., 1998; Smith et al., 2007). Globally, N_2O emissions from agricultural soils increased by about 19% between 1990 and 2010 While N_2O emissions from all sources grew only 4%. In 2010, soil N_2O emissions account for approximately 56% of the global N_2O emissions, up from 51% in 1990.[1] In contrast to soil N_2O, where there are sizable annual fluxes that depend on human activity, soil organic C stocks are assumed to be approximately in equilibrium.[2]

The marginal abatement cost curves presented in this chapter consider mitigation strategies that apply to only a fraction of the total emissions from agriculture. Specifically, the following categories are included:

- Direct and indirect emissions from mineral-based cropland soils processes
  - Synthetic and organic fertilization
  - Residue N
  - Mineralization and asymbiotic fixation, based on temperature and moisture, etc.
- Major crops supplemented by selected similar minor crops
  - Barley (plus rye)
  - Maize (plus green corn)
  - Sorghum
  - Soybeans (plus lentils, other beans)
  - Wheat (plus oats)

In addition, compared to the estimates typically developed for GHG inventories, the emissions presented in this chapter will be lower because the following types of emissions are excluded due to data and resource limitations:

- Drainage of organic soils.
- Grassland soils
- Other crops not mentioned above (e.g. vegetables)
- Restoration of degraded lands
- Burning of residues or biofuel

The focus is on emissions from major crops, which is consistent with our evaluation of mitigation options that can be applied to mitigate emissions from these major crops in this chapter.

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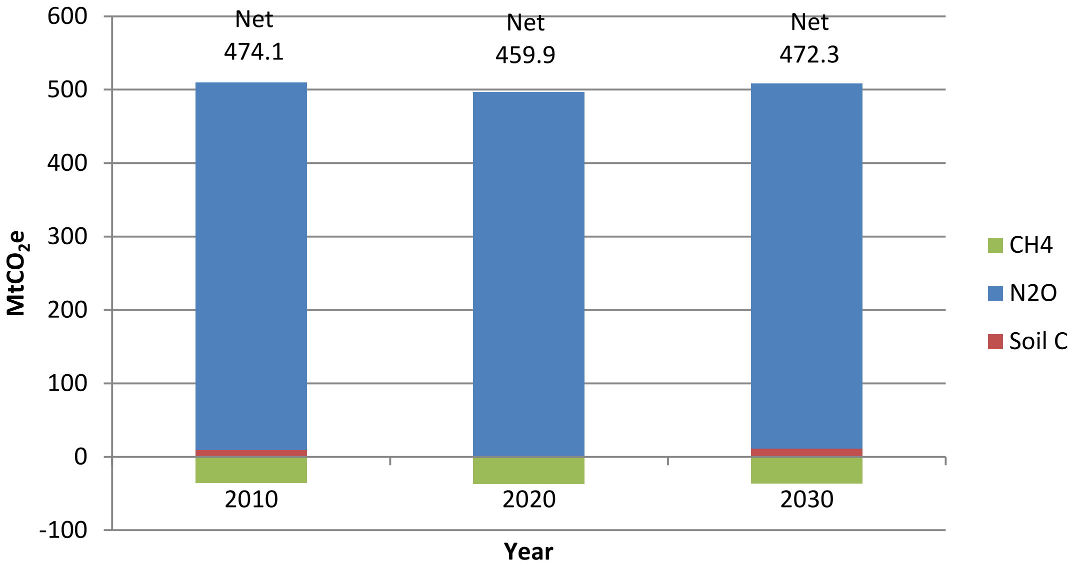
[1] Global total N_2O emissions were 3240.7 $MtCO_2e$ in 1990 and 3,519.6 $MtCO_2e$ in 2010. Agricultural soils total N_2O emissions were 1,658.1 $MtCO_2e$ in 1990 and 1,969.0 MtCO2e in 2010 (USEPA, 2012).

[2] Major changes in soil C occurred when land was first cultivated, but changes associated with agricultural soil management are approximately balanced at a global scale based on current management and land use change trends (Smith et al., 2007).

For the period 2010—2030 a business-as-usual forecast was constructed using projected growth rates in acreage, output, prices, yields, population, and GDP by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Nelson et al., 2010). The IFPRI IMPACT model projections provide a set of prices consistent with population and productivity assumptions for the MAC analysis.[3,4]

Figure 1-1 presents projected baseline N_2O and CH_4 emissions and changes in soil organic carbon from non-rice cropland soils; As shown in Figure 20-1, N_2O emissions from global non-rice cropland soils are projected to be 506, 500 and 504 million metric tons of CO_2 equivalent ($MtCO_2e$) in 2010, 2020 and 2030, respectively.[5] Non-rice cropland soils are a net sink for methane, sequestering approximately 38 $MtCO_2e$ of CH_4 per year. The estimated net changes in soil organic carbon suggest that the carbon stock changes are roughly balanced at the global scale.

Figure 1-1: Global Baseline Emissions from Non-Rice Croplands by GHG: 2010-2030



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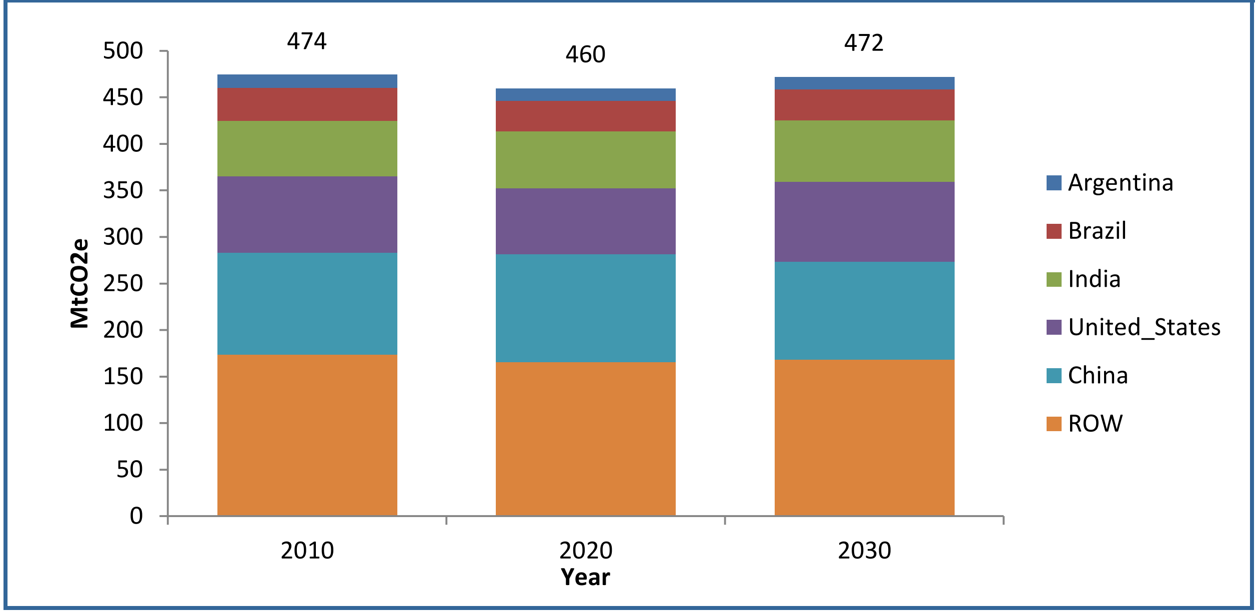
[3] The IMPACT outputs separated the world into 116 regions, with larger countries defined individually and smaller countries combined into regions. A mapping was created between IMPACT regions and the 195 countries in this analysis, using shares of country-level Non-Rice Croplands population in 2010 based on USEPA (2012) to disaggregate regional projections from the IMPACT model to individual countries within each region.

[4] The business as usual forecast excludes such potential drivers as deforestation, biofuels expansion and changes in consumer preferences for meat.

[5] The relative constant GHG emissions projected in the baseline are mainly driven by the DAYCENT modeling that assumes the same management practices are applied throughout the study period as well as relatively small changes in demand in the IMPACT model projections.

Figure 1-2 presents the projected net GHG emissions (N_2O and CH_4) from the top-five emitting countries. The top 5 countries of China, India, the United States, Brazil and Argentina represent about 63% of global net emissions from cropland in 2010.

Figure 1-2: Baseline Net GHG Emissions from Non-Rice Croplands, Top Five Emitting Countries



Note: ROW indicates Rest of the World

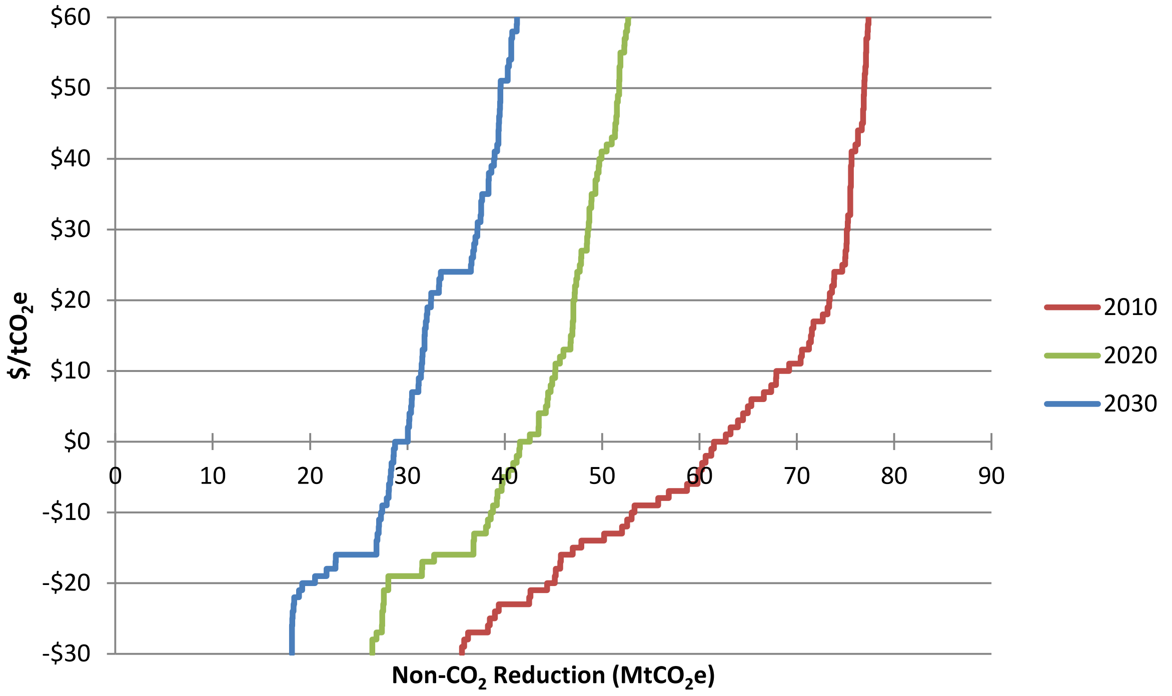
Table 1-1: Projected Net GHG Baseline Emissions from Non-Rice Croplands by Country: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	109	123	116	115	105	-0.2%
U.S.A	82	80	71	84	86	0.2%
India	60	58	61	61	66	0.5%
Brazil	35	32	33	33	34	-0.2%
Argentina	14	16	14	16	13	-0.2%
Rest of Regions						
Asia	31	26	27	27	27	-0.8%
Africa	31	26	30	28	29	-0.3%
Europe	62	56	59	63	60	-0.2%
Middle East	4	9	7	9	10	4.2%
Central & South America	13	14	15	15	15	0.8%
Eurasia	18	14	15	15	13	-1.4%
North America	15	15	14	16	14	-0.2%
World Totals	474	470	460	482	472	0.0%

Figure 1-3 presents the MAC curves for the global non-rice croplands, in 2010, 2020 and 2030. The non-rice croplands MAC curves presented in this chapter are distinctive because they show less abatement potential in 2030 than in 2010 – the 2030 curve is to the left or "inside" the 2020 and 2010 curves. This is due to the effect of soils becoming "saturated" with C and reaching a new equilibrium within a few years of a management change. In other words, the 2020 mitigation estimate is the change from the baseline emissions in 2020, *for a management change started in 2010*.

MAC analysis of the mitigation options described above suggests that at a relatively low carbon price of $5 per ton of CO_2 equivalent ($/$tCO_2e$), net GHG abatement potential for global non-rice cropland soils is approximately 65 $MtCO_2e$, or about 13% of its baseline net emissions of 476 $MtCO_2e$ in 2010. Mitigation potential at $5/ tCO_2e reduces to 10% of the sector's baseline emissions in 2020 and 6% in 2030.

Figure 1-3: Global MAC Curve for Net GHG Reductions from Non-Rice Cropland Soils



The following section offers a brief description of the model used. Section IV.20.3 presents selected abatement technologies, their technical specifications, costs and potential benefits. Section IV.20.4 discusses the MAC analysis and estimated abatement potential and at global and regional levels. The final section discusses uncertainties and limitations.

V.1.2 Emissions from Non-Rice Croplands

V.1.2.1 Methodology

The DAYCENT ecosystem model was used to estimate crop yields, N_2O and CH_4 emissions, and soil C stocks in this analysis. DAYCENT is a process-based model (Parton et al., 1998; Del Grosso et al., 2001) that simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil by representing the influence of environmental conditions on these fluxes including soil characteristics and weather patterns, crop and forage qualities, and management practices. DAYCENT utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), with refinement to simulate C dynamics at a daily time-step. Key processes simulated by DAYCENT include crop production, organic matter formation and decomposition, soil water and temperature regimes by layer, in addition to nitrification and denitrification processes. DAYCENT has been evaluated in several studies (e.g., Del Grosso et al. 2002, 2005, 2009) and has also been recently adopted by EPA to develop the soil C and soil estimates for the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2013) submitted to the UNFCCC.

Crop yields, direct N_2O and CH_4 emissions, and soil organic C stock changes were simulated by DAYCENT at a 0.5°grid resolution. Indirect N_2O emissions[6] were estimated simulated amounts of nitrate leaching, N runoff in overland water flow, and NO_x emissions from a site according to the DAYCENT model[7] combined with the IPCC default factors for indirect N_2O emissions (De Klein et al., 2006). In order to represent the longer term effect of cultivation on soil C, simulations started in 1700 after a simulation of 3000 years of native vegetation, which is a similar procedure to the methods applied in the US Greenhouse Gas Inventory for agricultural soil C and N_2O (USEPA, 2013).

For this study, a number of data sources were used to establish the business-as-usual baseline conditions and simulate alternative management options for the global non-rice croplands. Weather data were based on a dataset generated by the North American Carbon Program at a 0.5°resolution with daily minimum and maximum temperatures and daily precipitation.[8] The soils data were based on the FAO Digitized Soil Map of the World (FAO 1996). Major cropland areas of the world were simulated according to a global cropland map developed by Ramankutty et al. (2008), with grid cells with less than 5% cropland area excluded in the analysis.

Native vegetation data are described in Cramer and Field (1999) and Melillo et al. (1993). Natural vegetation was converted to cropland in the DAYCENT simulations at an approximate first year of cultivation, based on historical records compiled by Ramankutty and Foley (1998) and Ramankutty et al., (2008).

Due to lack of global data availability, low input crop production with intensive tillage practices were assumed prior to 1950, consistent with typical practices in that time period. From 1950 to 2010, management was based on data including tillage and residue management, weeding practices, mineral N fertilization, manure N amendments to soils, and irrigation. Crop planting and harvest dates were based on Sacks et al. (2008). Crops were assumed to grow in monoculture due to insufficient data for determining typical crop rotation practices from the global datasets. Maize and sorghum were double-cropped in some regions based on Sacks et al. (2008). Model performance was evaluated by comparing simulated crop yields to observed crop yields (Monfreda et al. 2008), and minor adjustments were made to parameters in order to be reasonably consistent with the observed yields. More detail on the input data and simulation framework is provided in Appendix O.

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[6] N_2O emissions occurring with transport of N from one site to another where N_2O emissions occur with N addition.

[7] The same method as used in the US National Greenhouse Gas Inventory (USEPA, 2013).

[8] The Multi-Scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) developed consistent weather data in order to “isolate, interpret, and address differences in process parameterizations among [terrestrial biospheric models]” Source: http://nacp.ornl.gov/MsTMIP.shtml.

Global DAYCENT modeling was carried out for irrigated and non-irrigated production systems for maize, wheat, barley, soybean and sorghum. Crop yields and GHG fluxes were simulated at the 0.5°resolution for periods 2000-2010 and 2011-2030 with five-year increments. A baseline scenario is established for each crop production system assuming business-as-usual management practices described above. Seven mitigation scenarios were then analyzed (see Section 3.4 below).

Emissions estimated by the DAYCENT model for major crop types (maize, wheat, barley, sorghum, soybean and millet) were based on emissions per unit (m2) of physical area in each in each 0.5° x 0.5° grid cell, and so were multiplied by an estimate of cropland area in each grid cell to compute total GHG emissions. We approximated crop-specific areas using harvested area data. First, crop-specific harvested areas for each 0.5° x 0.5° grid cell were estimated from Monfreda et al. (2008). For each grid cell where we simulated double-cropping for maize or sorghum, we reduced maize or sorghum harvested area by 50%. Next, harvested areas for analogous crops were added to areas of the major crop types (i.e., oats with wheat, rye with barley, green corn with maize, and lentil, green bean, string bean, broad bean, cow pea, chickpea and dry bean with soybeans) to increase the coverage of cropland area. The sums of harvested areas fractions computed in this manner were less than total cropland areas (Ramankutty et al. 2008) for all but 1.6% of grid cells. In the last step, total harvested area was scaled to match at the country scale data on harvested areas reported in FAOSTAT. By including analogous crops and matching FAOSTAT harvested areas, the cropland area simulated by DAYCENT was about 61% of the global non-rice cropland areas reported by FAOSTAT.

Projected baseline emissions and crop production were then established for both irrigated and rainfed production systems using simulated yields and GHG emissions rates from DAYCENT model and adjusting with projected growth rates of these production systems by IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. In DAYCENT, crop production areas were held constant at the 2010 level to obtain the biophysical effects of management practice changes on crop yields and GHG fluxes. Projected acreage changes from IMPACT model reflect socio-economic drivers such as population growth and technological changes to meet global food demand (Nelson et al., 2010).

V.1.3 Abatement Measures and Engineering Cost Analysis

V.1.3.1 Mitigation Technologies

The mitigation options evaluated in this analysis were based on review of the literature to identify the most promising options, while also taking data availability and potential for modeling within DAYCENT into consideration. The mitigation options represent alternative management practices that would alter crop yields and the associated GHG emissions, including adoption of no-till management, split N fertilization applications, application of nitrification inhibitors, increased N fertilization (20% increase over business-as-usual), decreased N fertilization (20% reduction from business-as-usual), and 100% crop residue incorporation.

The N management practices (split N fertilization, nitrification inhibitors, increased and decreased N fertilization) influence N_2O emissions in addition to soil organic C stocks due to reduced or enhanced C inputs associated with the level of crop production. Smith et al. (2007) estimated that 89% of the overall technical potential for mitigation of agricultural greenhouse gas emissions is associated with carbon sequestration in soils. Although soil organic C stock fluxes are negligible in the baseline, there is considerable opportunity to modify stocks in the future. Levels of soil organic matter and in particular soil carbon both influence, and are influenced by cropland productivity. Other things being equal, higher crop yields may increase soil C wherever more crop residue can be incorporated into the soil. Similarly, reducing crop residue removal would impact soil organic C stocks by changing the amount of C input to the soil. Practices such as adoption of conservation tillage, restoration of degraded lands, improved water and nutrient management, and cropping intensification can increase soil carbon by enhancing C inputs to soils from greater crop production or decrease the losses of C from soils with lower decomposition rates (Paustian et al. 1997; Six et al., 2000).

No-Till Adoption

All cultivation and field preparation events were removed except for seeding, which occurred directly into the residue.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: There are reductions in labor costs associated with the reduction in field preparation that are based on data from U.S. Department of Agriculture (USDA) Agricultural Resource Management Survey (ARMS) data, which provides labor estimates for conventional and conservation tillage on both irrigated and rain-fed land by major crop. Conversion to no-till would require purchasing equipment for direct planting. However, if this equipment is purchased in place of equipment used for traditional tillage, there may be little incremental capital cost associated with no-till. Some crop budgets actually indicate lower capital costs for no-till because of the need for fewer passes over the field, which lead to reduced equipment depreciation. Thus, no incremental capital costs were assumed for no-till adoption.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

Reduced Fertilization

This option reduced baseline fertilizer application levels by 20%.

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option reduces operation costs by the value of fertilizer withheld.
- Additional Factors: In cases where yields decrease as a result, the reduction in production is valued at the market price. No tax or other benefits are included in this option.

Increased Fertilization

This option increased baseline fertilizer application levels by 20%.

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option increases operation costs by the value of additional fertilizer used.
- Additional Factors: In cases where yields increase as a result, production is valued at the market price. No tax or other benefits are included in this option.

Split N Fertilization

Under this option, the baseline N application amount was applied in three separate and equal amounts (planting day, 16 days after planting day, and 47 days after planting day) instead of once on planting day.[9]

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option was assumed to require 14% more labor to account for additional passes over the fields to apply fertilizer multiple times rather than only once.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

Nitrification Inhibitors

The baseline N application amount was applied once annually on date of planting. Nitrification inhibitors were applied at time of fertilization, and reduced nitrification by 50% for 8 weeks[10].

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: The costs of this option include the cost of the nitrification inhibitor, assumed to be $20 per hectare for the United States (Scharf et al., 2005) and scaled to other regions.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

100% Residue Incorporation

In this option, all crop residue was assumed to remain after harvest. This option serves to evaluate how reducing removals would impact soil organic C stocks.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: No cost is associated with this option.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

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[9] Following Del Grosso et al. (2009).

[10] Following Del Grosso et al. (2009) and Branson et al. (1992).

Table 1-2: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric tons of Grain per Hectare)

	2010	2015	2020	2025	2030
Maize					
Base Yield	3.64	3.64	3.64	3.59	3.6
No-Till	0	-0.25	-0.17	-0.12	-0.07
Optimal N fertilization*	0	2.9	3.05	3.1	3.08
Split N Fertilization	0	0.16	0.17	0.19	0.18
100% Residue Inc.	0.22	0.23	0.24	0.24	0.24
Nitrification Inhibitors	0	-0.01	-0.01	-0.01	-0.01
Reduced Fertilization	-0.05	-0.36	-0.39	-0.4	-0.4
Increased Fertilization	0.04	0.28	0.29	0.31	0.31
Millet					
Base Yield	1.16	1.17	1.14	1.11	1.12
No-Till	0	-0.09	-0.07	-0.05	-0.03
Optimal N fertilization*	0	2.38	2.59	2.55	2.61
Split N Fertilization	0	0.09	0.09	0.09	0.08
100% Residue Inc.	0.09	0.08	0.09	0.09	0.08
Nitrification Inhibitors	0	0.02	0.03	0.03	0.03
Reduced Fertilization	-0.01	-0.08	-0.09	-0.1	-0.1
Increased Fertilization	0.01	0.08	0.09	0.09	0.09
Sorghum					
Base Yield	2.34	2.34	2.35	2.33	2.32
No-Till	0	-0.18	-0.13	-0.1	-0.06
Optimal N fertilization*	0	3.07	3.27	3.19	3.25
Split N Fertilization	0	0.14	0.14	0.13	0.14
100% Residue Inc.	0.15	0.15	0.17	0.16	0.17
Nitrification Inhibitors	0	-0.02	-0.03	-0.02	-0.02
Reduced Fertilization	-0.03	-0.22	-0.25	-0.26	-0.27
Increased Fertilization	0.03	0.19	0.22	0.22	0.23
Winter Wheat					
Base Yield	2.94	2.92	2.89	2.8	2.87
No-Till	0	-0.13	-0.11	-0.07	-0.05
Optimal N fertilization*	0	1.55	1.82	1.87	1.78
Split N Fertilization	0	0.09	0.1	0.11	0.11
100% Residue Inc.	0.1	0.11	0.12	0.13	0.12
Nitrification Inhibitors	0	0.03	0.04	0.04	0.05
Reduced Fertilization	-0.01	-0.22	-0.26	-0.25	-0.27
Increased Fertilization	0	0.19	0.2	0.2	0.21

(continued)

Table 1-2: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric tons of Grain per Hectare) (continued)

	2010	2015	2020	2025	2030
Spring Wheat					
Base Yield	2.85	2.94	2.92	2.85	2.83
No-Till	0	-0.16	-0.13	-0.1	-0.08
Optimal N fertilization*	0	1.49	1.46	1.4	1.36
Split N Fertilization	0	0.07	0.08	0.08	0.08
100% Residue Inc.	0.1	0.11	0.11	0.11	0.11
Nitrification Inhibitors	0	0.02	0.03	0.03	0.03
Reduced Fertilization	-0.03	-0.2	-0.22	-0.21	-0.21
Increased Fertilization	0.02	0.14	0.15	0.14	0.14
Winter Barley					
Base Yield	3.55	3.59	3.58	3.5	3.57
No-Till	0	-0.2	-0.21	-0.15	-0.1
Optimal N fertilization	0	2.64	3.11	3.07	3
Split N Fertilization	0	0.04	0.06	0.06	0.05
100% Residue Inc.	0.35	0.37	0.39	0.39	0.39
Nitrification Inhibitors	0	0.01	0.03	0.03	0.03
Reduced Fertilization	0	-0.34	-0.39	-0.41	-0.43
Increased Fertilization	0	0.31	0.35	0.36	0.38
Spring Barley					
Base Yield	2.76	2.83	2.79	2.77	2.77
No-Till	0	-0.29	-0.24	-0.2	-0.17
Optimal N fertilization*	0	1.8	1.8	1.67	1.63
Split N Fertilization	0	0.08	0.09	0.09	0.08
100% Residue Inc.	0.19	0.21	0.22	0.21	0.21
Nitrification Inhibitors	0	0.01	0.02	0.02	0.02
Reduced Fertilization	-0.04	-0.28	-0.31	-0.31	-0.32
Increased Fertilization	0.04	0.24	0.26	0.25	0.25
Soybeans					
Base Yield	2.9	2.95	2.94	2.92	2.92
No-Till	0	-0.02	-0.02	-0.01	-0.01
Optimal N fertilization*	0	0.06	0.07	0.07	0.07
Split N Fertilization	0	0	0	0	0
100% Residue Inc.	0.02	0.02	0.02	0.02	0.02
Nitrification Inhibitors	0	0	0.01	0.01	0.01
Reduced Fertilization	0	-0.01	-0.01	-0.01	-0.01
Increased Fertilization	0	0.01	0.01	0.01	0.01

*Note: Optimal N Fertilization, discussed below, is excluded from the main MAC analysis and presented for information only

V.1.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-CO_2 sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

This section describes the general modeling approach applied in this sector, which serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

V.1.4.1 Estimate Abatement Measure Costs and Benefits

As a general framework of the MAC analysis, the break-even price for each mitigation option is calculated by setting total benefits (i.e., higher yields) equal to total costs of a given mitigation option. This framework, also referred to as the International Marginal Abatement Cost (IMAC) model, is documented in USEPA (2006) and Beach et al. (2008).

V.1.4.2 MAC Analysis Results

Global abatement potential in the Non-Rice Croplands sector equates to approximately 6 to 13% of its total annual emissions between 2010 and 2030 at a relatively low carbon price of $5 per ton of CO_2 equivalent ($/$tCO_2e$). Table 1-3 presents mitigation potential at selected break-even prices for 2030. GHG mitigation and its cost-effectiveness vary significantly by country or region. Figure 1-4 displays the MAC curve of the top-five emitting countries in 2010 and 2030.

Table 1-3: Abatement Potential at Selected Break-Even Prices in 2030 (No "Optimal Fertilization "Scenario)

	Break-Even Price ($/$tCO_2e$)										
Country/Region	–10	–5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
China	11.2	11.2	11.2	11.2	11.3	11.3	11.3	12.1	12.1	12.1	12.8
U.S.A	5.4	5.4	5.5	5.5	5.5	5.5	5.5	8.7	8.7	8.8	10.9
India	2.5	2.9	3.1	3.1	3.6	3.6	3.6	3.6	4.0	4.0	5.3
Brazil	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.1
Argentina	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	1.0
Rest of Region											
Africa	1.7	1.9	2.1	2.2	2.2	2.2	2.2	2.3	2.3	2.8	3.9
Asia	1.5	1.6	1.8	1.9	1.9	2.0	2.0	2.0	2.3	2.5	3.0
Central & South America	0.3	0.4	0.4	0.5	0.6	0.8	0.8	0.8	0.9	1.1	1.8
Eurasia	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	1.7	2.3	2.7
Europe	3.0	3.0	3.4	3.5	3.6	3.6	3.8	4.1	4.3	6.0	8.7
Middle East	0.2	0.3	0.8	0.8	0.8	0.8	1.3	1.3	1.4	1.4	1.7
North America	0.6	0.6	0.6	0.6	0.8	0.8	0.8	0.9	0.9	1.0	1.9
World Total	27.4	28.3	30.0	30.4	31.5	31.8	32.4	37.2	39.6	43.0	55.8

Figure 1-4: Marginal Abatement Cost Curve for Top-Five Emitting Countries in 2010 and 2030

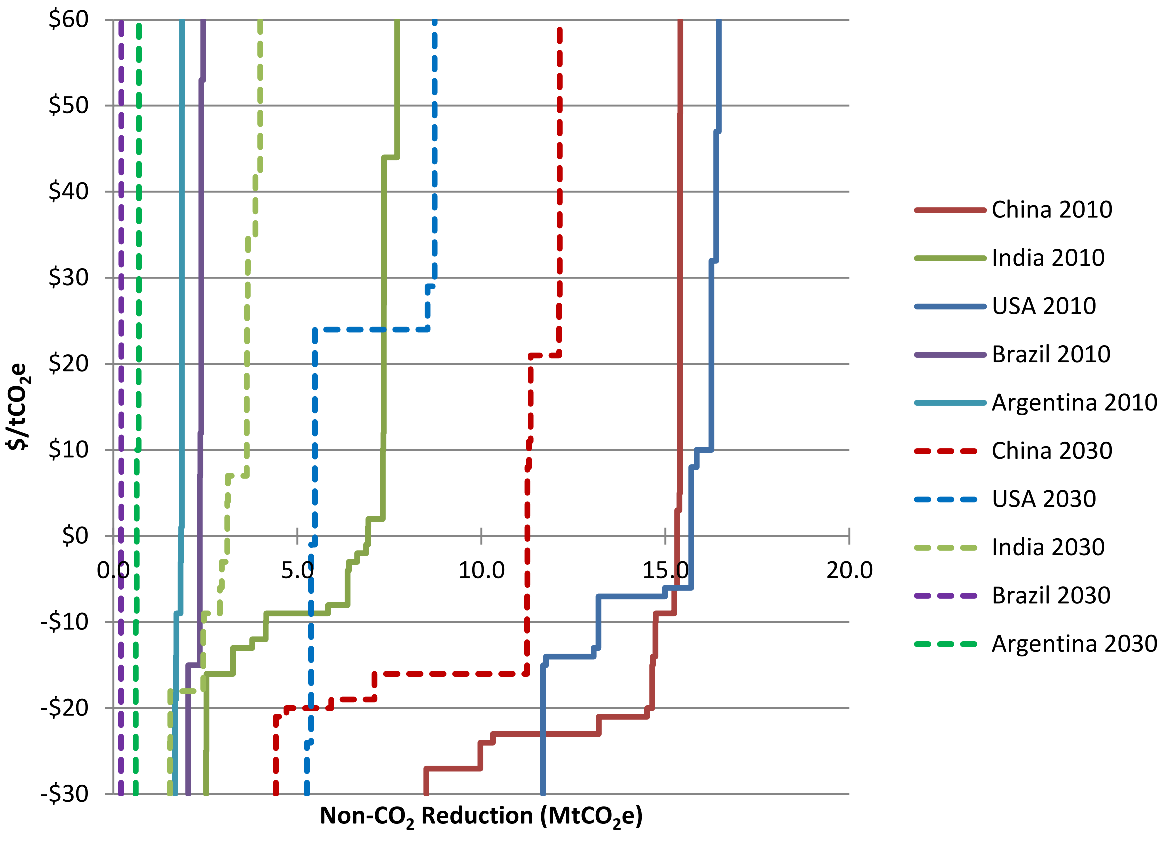

Table 1-4 below presents a summary of estimated global total mitigation potential by mitigation option. Overall the MAC analysis results suggest that No-till is the most effective strategy for GHG mitigation in cropland soil management.[11] This option accounts for approximately 70% of the total global mitigation potential in 2010 and 43.7% in 2030. The second most significant mitigation option is reduced fertilization, accounting for about 16% of the global total mitigation potential in 2010 and 40% in 2030. Adoption of nitrification inhibitors and split fertilization may also make significant contributions to net GHG reductions from cropland soil management.

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[11] As discussed above, mitigation potential from adoption of no-till practice is likely over-estimated with 100% conventional tillage assumed in the business-as-usual baseline.

Table 1-4: Global Total Abatement Potential from Cropland Soils by Measure ($MtCO_2e$) ("Optimal N Fertilization" Strategy excluded)

	GHG Mitigation by Option (total all prices)					
	2010		2020		2030	
Reduced Fertilization	14.05	16%	18.09	26%	22.39	40.1%
Increased Fertilization	0.30	0%	0.03	0%	0.00	0.0%
100% Residue Incorporation	0.33	0%	0.18	0%	0.04	0.1%
Nitrification Inhibitors	7.08	8%	6.46	9%	6.66	11.9%
Split N Fertilization	4.38	5%	3.14	4%	2.36	4.2%
No-Till Adoption	60.82	70%	42.47	60%	24.40	43.7%
Optimal N Fertilization	0.00	0%	0.00	0%	0.00	0.0%
TOTAL	86.94	100%	70.37	100%	55.85	100.0%

The relative mitigation potentials of no-till and reduced fertilization illustrate the difference between dynamics of soil C and N_2O and are worth a closer look. No-till dominates the mitigation potentials in the early years, owing to its large effect on soil C. However, this dominance disappears over time as soils become "saturated" with C. By 2030, the mitigation potential (limited to N_2O) of reduced fertilization nearly equals that of no-till. Over an even longer time scales, only the N_2O flux remains as soils reach a new equilibrium level of Soil C.

V.1.5 Sensitivity Analysis

We tested the sensitivity of the results by adding an additional "Optimal N Fertilization" option, which has substantial effects on global yields and emissions.

Optimal N fertilization

This option allows the model to maximize soil carbon through optimization of fertilizer inputs, giving a "best case" result of the application of existing technology and crop patterns. Of course, baseline levels vary widely from this optimum with some regions over-applying N and many under-applying N relative to crop needs. This case shows what could be achieved if nutrient stress is removed at each time step.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: Due to the large number of ways this option might be put in practice, costs are limited to the change in N used.
- Additional factors: In cases where yields increase as a result, production is valued at the market price. No tax or other benefits are included in this option.

This analysis resulted in the global MAC curve shown in Figure 1-5, and summarized in Table 1-5. With Optimal N Fertilization included in the analysis, global mitigation increases from a maximum of 86 Mt to 129 Mt in 2010. Global mitigation in 2030 increases from a maximum of 56 Mt to about 86 Mt.

Overall the MAC analysis results suggest that optimal fertilization to achieve maximum crop yields is potentially the single most significant source of GHG mitigation in cropland soil management. This option accounts for approximately 44% of the total global mitigation potential in 2010 and 2030. The second most significant mitigation option is no-till practice, accounting for about 39% of the global total mitigation potential.[12] Reduction in N fertilizer application and adoption of nitrification inhibitors would also make substantial contributions to net GHG reductions from cropland soil management.

Figure 1-5: Global Abatement Potential in Non-rice Croplands Management: 2010, 2020, and 2030 (Includes "Optimal N Fertilization" Strategy)

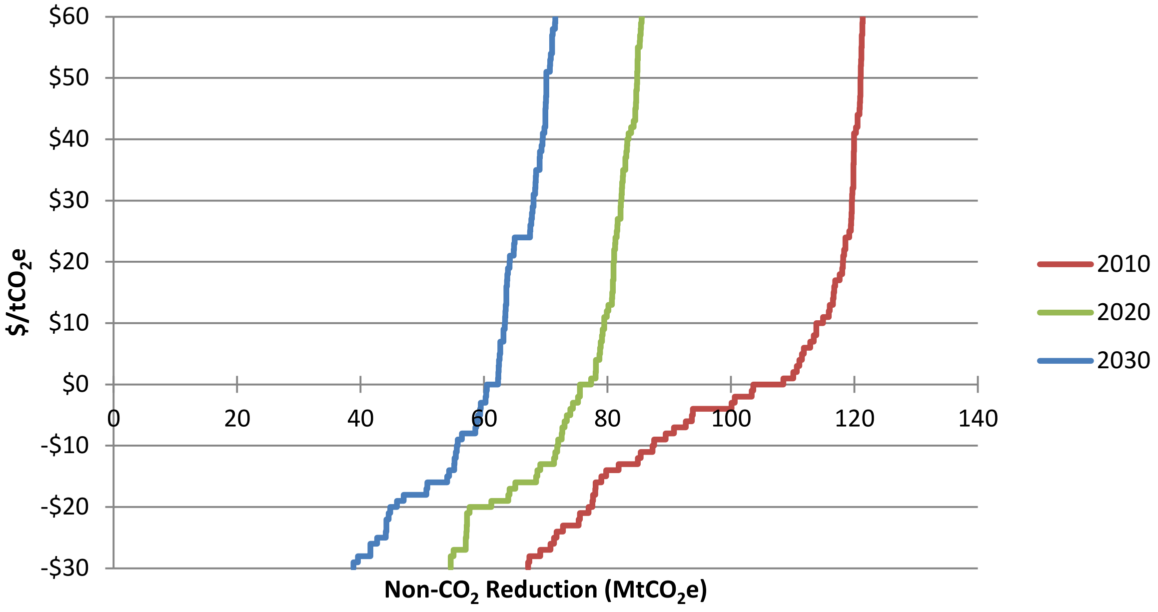

Table 1-5: Global Total Abatement Potential from Cropland Soils by Measure (MtCO$_2$e) (Includes "Optimal N Fertilization" Strategy)

	GHG Mitigation by Option (total all prices)					
	2010		2020		2030	
Reduced Fertilization	11.1	9%	0.0	14%	17.7	21%
Increased Fertilization	0.2	0%	0.0	0%	0.0	0%
100% Residue Incorporation	0.3	0%	0.1	0%	0.0	0%
Nitrification Inhibitors	6.0	5%	5.6	6%	6.1	7%
Split N Fertilization	3.6	3%	2.7	3%	2.2	3%
No-Till Adoption	50.8	39%	35.4	35%	20.9	25%
Optimal N Fertilization	57.3	44%	42.2	42%	37.7	45%
TOTAL	129.4	100%	86.1	100%	84.7	100%

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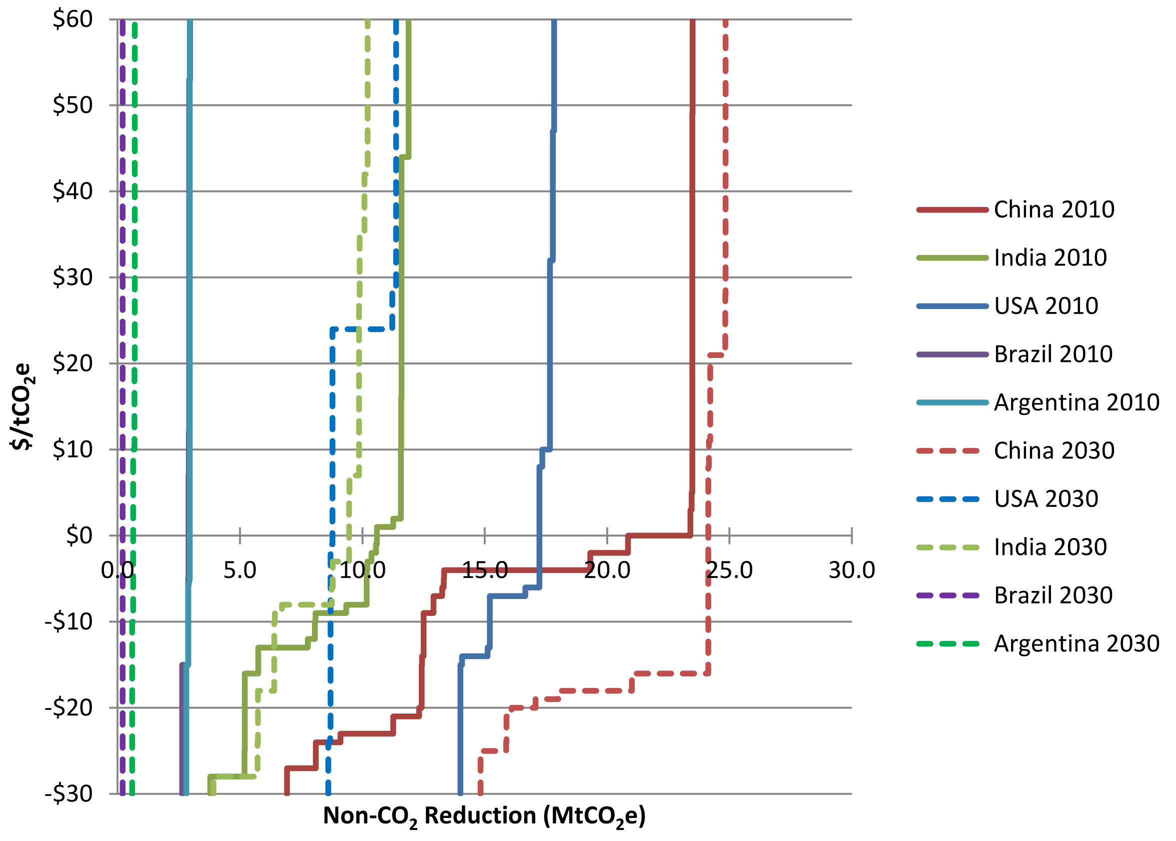
[12] As discussed above, mitigation potential from adoption of no-till practice is likely over-estimated with 100% conventional tillage assumed in the business-as-usual baseline.

Figure 1-6 shows the effect on the top-5 countries. With "Optimal N Fertilization" included as a strategy, China has the largest mitigation potential of any country and is also among the few countries that have mitigation potential that increases over the 2010-2030 period. This appears to be related to fertilizer use that is much higher than optimal.[13] This suggests that N_2O emissions may be reduced without a yield, or soil C, penalty.

Figure 1-6: Marginal Abatement Cost Curve for Top 5 Emitters in 2010, 2030 (Includes "Optimal N Fertilization" Strategy)



V.1.5 Uncertainties and Limitations

Given the complexities of the global crop production sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Optimistic assumptions on technology adoption.*** Mitigation technologies represent technical potentials. The analysis assumes that if mitigation technology is considered feasible in a country

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[13] In the DAYCENT optimal fertilization scenario, where the model determined the optimal fertilizer rates, fertilizer use typically decreased in China between 30 and 50% for major crops as compared to baseline levels. N_2O emissions also declined.

or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially slow the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.

- ***Availability and quality of data to represent the highly complex and heterogeneous crop production systems of the world.*** Compared to the previous EPA marginal abatement cost curve analysis (USEPA, 2006), there are major improvements in the datasets used to represent the global crop production systems and the business-as-usual baseline conditions. However, data in some areas, such as management practices which have significant influence on the GHG fluxes, are not always available for all countries or regions. Approximations had to be made based on limited literature or expert judgment. Moreover, collecting and developing regionally specific cost estimates of emerging and/or not widely adopted management practices or mitigation measures has been a challenge and in some cases global datasets had to be used.
- ***Biophysical modeling uncertainties.*** The evaluation of simulated crop yields against observed yields suggests that DAYCENT modeling performance varies by crop[14], leading to potential biases in estimated GHG emissions. Model structure is found to be the largest contributor to uncertainty in simulation results using DAYCENT, typically more than 75% of overall uncertainty in estimates (Ogle et al. 2010, Del Grosso et al. 2010). Further model evaluation will be carried out to understand potential model bias and prediction error using empirical based procedure discussed in Ogle et al. (2007). In addition, soil carbon, which has a significant impact on the net GHG emissions and mitigation potential from the sector, is particularly challenging to simulate given the lack of monitoring data at the global scale. Sensitivity tests would be useful to assess how alternative modeling approaches and assumptions may influence modeling results.
- ***Potential interactions of multiple mitigation measures are not fully addressed in this analysis.*** In this analysis, mitigation options are applied to independent segments of the crop production systems to avoid double counting. In reality, multiple mitigation options can be applied, and their order of adoption and potential interactions may affect the aggregate GHG mitigation. Alternative approach should be investigated to provide more realistic representation of economic applicability of potential mitigation measures.

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[14] Overall, simulated yields for maize agree reasonably well with observed yields; simulated average yields for wheat, barley and sorghum are lower than observed yields; simulated average yields for soybean are above observed yields.

References

Beach, R.H., DeAngelo, B., Rose, S., Salas, W., Li, C., DelGrosso, S. (2008). Mitigation potential and costs for global agricultural greenhouse gas emissions. *Agricultural Economics* 38(2): 109-115.

Bronson, K.F., Mosier, A.R., Bishnoi, S.R., 1992. Nitrous oxide emissions in irrigated corn as affected by nitrification inhibitors. Soil Sci. Soc. Am. J. 56, 161–165.

Cramer, W., Field, C.B., 1999. Comparing global models of terrestrial net primary production (NPP): overview and key results. *Glob. Change Biol.* 5 (Suppl. 1), 1–15.

De Klein, C., R.S.A. Novoa, S. Ogle, K.A. Smith, et al. 2006. Chapter 11: N_2O emissions from managed soil, and CO_2 emissions from lime and urea application. In *2006 IPCC guidelines for national greenhouse gas inventories, Vol. 4: Agriculture, forestry and other land use*, edited by S. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe. Kanagawa, Japan: IGES.

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S. 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer, M., et al. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management, p. 303-332, CRC Press, Boca Raton, Florida, USA.

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A., Schimel, D.S., 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. *Environmental Pollution* 116: S75-S83.

Del Grosso, S.J., A.R. Mosier, W.J. Parton and D.S. Ojima. 2005. DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. *Soil Tillage and Research* 83:9-24.

Del Grosso, S.J., D.S. Ojima, W.J. Parton, E. Stehfest, M. Heistemann, B. DeAngelo, S. Rose. 2009. Global Scale DAYCENT Model Analysis of Greenhouse Gas Mitigation Strategies for Cropped Soils. *Global and Planetary Change*, 67, 44-50.

Del Grosso, S., S.M. Ogle, W.J. Parton, and F.J. Breidt. 2010. Estimating uncertainty in N_2O emissions from US cropland soils. *Global Biogeochemical Cycles*, 24, GB1009, doi:10.1029/2009GB003544.

FAO, 1996. The Digitized Soil Map of the World Including Derived Soil Properties, CDROM. Food and Agriculture Organization, Rome.

Melillo, J.M., McGuire, A.D., Kicklighter, D.W., Moore III, B., Vörösmarty, C.J., Schloss, A.L. 1993. Global climate change and terrestrial net primary production. *Nature* 363, 234–240.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton (1993) "CENTURY Soil Organic Matter Model Environment." Agroecosystem version 4.0. Technical documentation, GPSR Tech. Report No. 4, USDA/ARS, Ft. Collins, CO.

Monfreda, C., N. Ramankutty and J.A. Foley. (2008), "Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000", *Global Biogeochemical Cycles*, Vol.22, GB1022, doi:10.1029/2007GB002947.

Mosier, A. R., J.M. Duxbury, J.R. Freney, O. Heinemeyer, K. Minami. 1998. Assessing and mitigating N2O emissions from agricultural soils. *Climatic Change* 40:7-38.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams and K. Paustian. 2007. Empirically based uncertainty associated with modeling carbon sequestration in soils. *Ecological Modelling* 205:453-463.

Ogle, S.M., F.J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian. 2010. Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. *Global Change Biology* 16:810-820.

Ogle, S.M., A. Swan and K. Paustian. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems and Environment* 149:37-49.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima (1987) "Analysis of factors controlling soil organic matter levels in Great Plains grasslands." *Soil Science Society of America Journal* 51:1173-1179.

Parton, W.J., J.W.B. Stewart, C.V. Cole. (1988) “Dynamics of C, N, P, and S in grassland soils: a model.” *Biogeochemistry* 5:109-131.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel (1994) “A General Model for Soil Organic Matter Dynamics: Sensitivity to litter chemistry, texture and management,” in *Quantitative Modeling of Soil Forming Processes*. Special Publication 39, Soil Science Society of America, Madison, WI, 147-167.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel (1998) “DAYCENT: Its Land Surface Submodel: Description and Testing”. *Glob. Planet. Chang*. 19: 35-48.

Paustian, K., H. P. Collins, and E. A. Paul. 1997. Management controls on soil carbon. Pages 15-49 in E. T. E. Paul E.A., K. Paustian, and C.V. Cole, editor. Soil organic matter in temperate agroecosystems: long-term experiments in North America. CRC Press, Boca Raton.

Robertson, G. P., E.A. Paul, and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289:1922-1925.

Ramankutty, N. and J.A. Foley. 1998. Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochemical Cycles* 12(4), 667-685.

Ramankutty et al. 2008. "Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000", *Global Biogeochemical Cycles*, Vol. 22, GB1003, doi:10.1029/2007GB002952.

Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty. 2010. Crop planting dates: an analysis of global patterns. *Global Ecology and Biogeography* 19, 607-620. DOI: 10.1111/j.1466-8238.2010.00551.x.

Six, J., E. T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32:2099-2103.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O’Mara, C. Rice, B. Scholes, O. Sirotenko,2007: Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You. (2010). Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. International Food Policy Research Institute: Washington, DC.

Smith, W.N., R.L. Desjardins, B. Grant, C. Li, R. Lemke, P. Rochette, M.D. Corre, and D. Pennock. (2002). Testing the DNDC model using N2O emissions at two experimental sites in Canada. *Canada Journal of Soil Science* 82:365-374.

U.S. Environmental Protection Agency (USEPA). 2006. *Global Mitigation of Non-CO$_2$ Greenhouse Gases*. EPA 430-R-06-005. Washington DC.

U.S. Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990–2030*. EPA 430-R-12-006. Washington DC.

U.S. Environmental Protection Agency (USEPA). 2013. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011*. Washington, D.C.

World Resources Institute (WRI). 2012. Climate Analysis Indicators Tool (CAIT) database. Available at http://www.wri.org/project/cait/.

V.2. Rice Cultivation

V.2.1 Sector Summary

Rice cultivation is an important global source of methane (CH_4) and nitrous oxide (N_2O) emissions. There are also changes in soil organic carbon (C) stocks and associated CO_2 fluxes. When paddy fields are flooded, decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil. Anaerobic decomposition of soil organic matter by methanogenic bacteria generates CH_4. Some of this CH_4 is dissolved in the floodwater, but the remainder is released to the atmosphere, primarily through the rice plants themselves. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through the floodwaters. In addition, as with other crops, human activities influence soil N_2O emissions through addition of synthetic and organic nitrogen fertilizers and other practices and soil C stocks through residue management as well as any practices that effect crop yields.

In 2010, the net global GHG emissions from rice cultivation were approximately 561 $MTCO_2e$. The top 5 emitting countries – India, Indonesia, Bangladesh, Vietnam, and China –accounted for 77% of the global total net emissions. Figure 2-1 displays the baseline net global GHG emissions for the rice sector. Net GHG emissions from rice cultivation are projected to grow by 33% to 750 $MTCO_2e$ between 2010 and 2030. There is a small amount of growth in emissions occurring in developing regions to meet the demand for rice products from growing populations and higher incomes, but the biggest contributor to the increase in net GHG emissions simulated between 2010 and 2030 is a reduction in the soil C sink over time. In the Denitrification-Decomposition (DNDC) model, there are fairly large increases in soil C in the initial periods in many countries as they have recently changed practices to incorporate more residues into the soil. However, as soil C moves to a new equilibrium, the incremental changes in future years become much smaller and offset a smaller portion of the non-CO_2 emissions.

Figure 2-1: Net GHG Emissions Projections for Rice Cultivation: 2000–2030

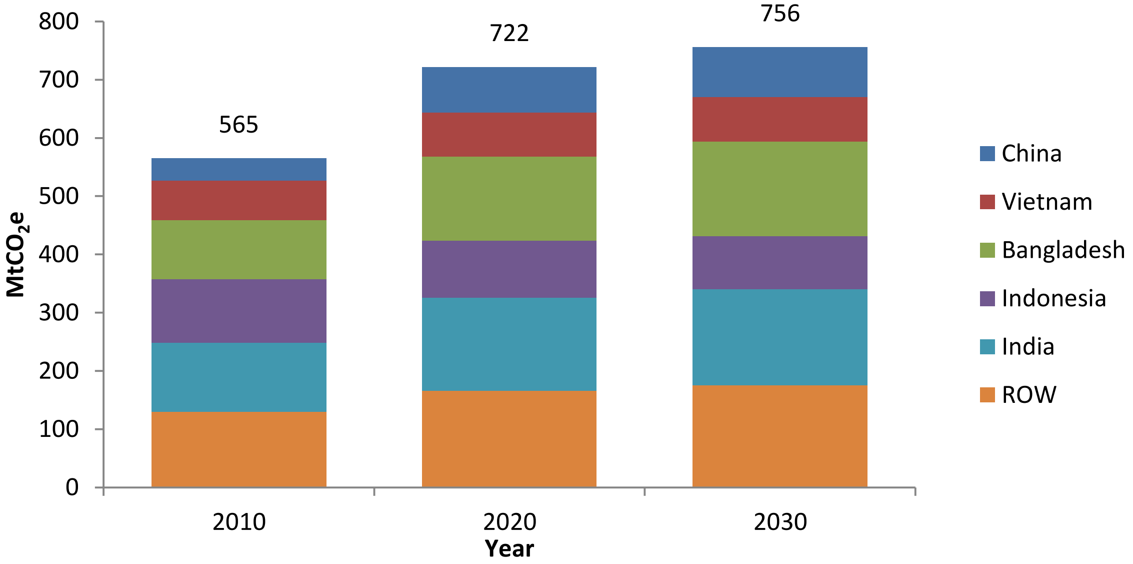


Table 2-1 shows the baseline CH_4, N_2O and soil carbon estimates for rice cropland by region. Rice cultivation results in emissions of CH_4 and N_2O, and these are offset by storage of carbon in the soil. In 2010, GHG emissions from rice cultivation include 484.1 $MTCO_2e$ CH_4 and 260.0 $MTCO_2e$ N_2O, offset by 179.2 $MTCO_2e$ of c stored in the soil, for net non-CO_2 emissions of 564.9.1 $MTCO_2e$, or about 5.8 percent of global non-CO_2 emissions (EPA, 2012).

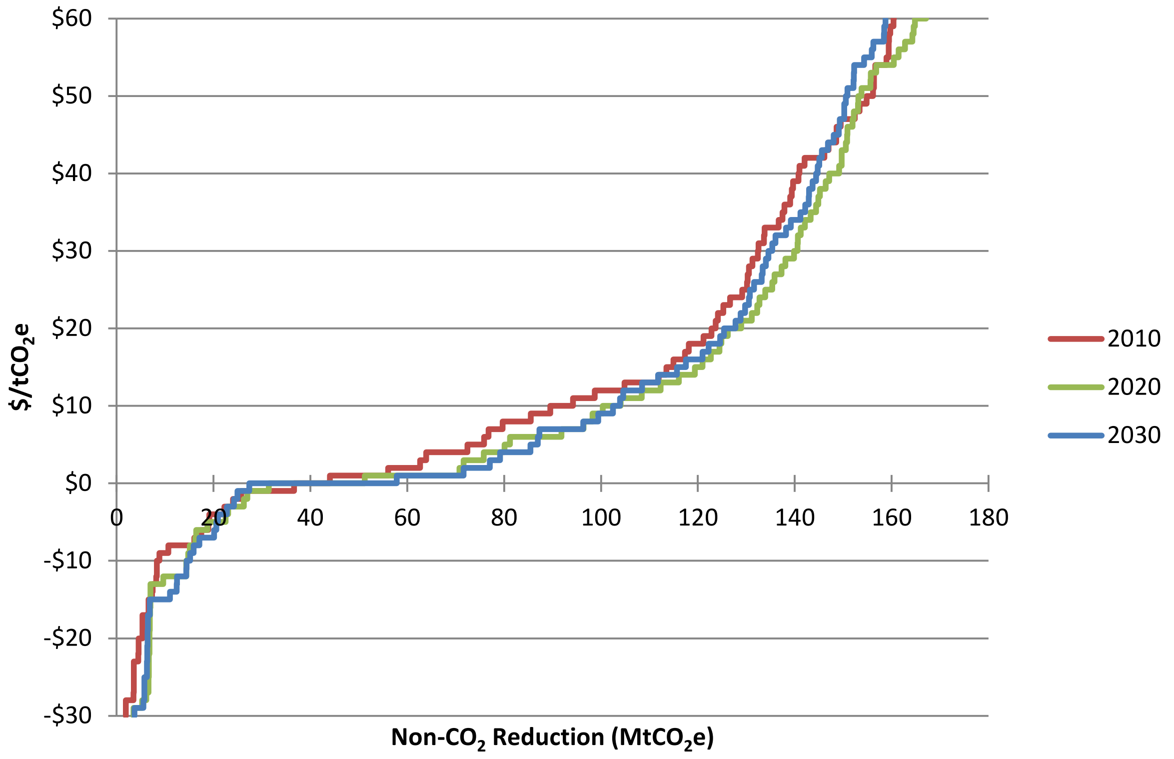
Table 2-1: Baseline CH_4, N_2O, and Soil Carbon Estimates for Rice Cropland for 2010, 2020 and 2030 by Region

	2010			2020			2030		
Country/Region	CH_4	N_2O	Soil C	CH_4	N_2O	Soil C	CH_4	N_2O	Soil C
Top 5 Emitting Countries									
India	91.2	76.7	-50	94	93.2	-27.5	89	94.1	-18.6
Indonesia	81.7	25.5	2.2	75.4	23.4	-0.5	70.7	22.1	-1.3
China	72.9	34.6	-69.4	72.8	36.7	-31.3	66.5	35.9	-16.9
Vietnam	47	25.7	-4.8	45.4	33.1	-2.8	44	34.5	-1.8
Bangladesh	54.4	63	-16	54.3	98.6	-8.5	54.5	112.4	-5
Rest of Region									
Africa	11.6	4.5	-3.8	12.6	6.2	-2.7	13.4	7	-2.1
Asia	79.8	22.8	-26.6	85.9	25.3	-13.2	85.9	25.9	-8.5
Central & South America	32.3	4.5	-5.1	33.5	5.3	-3.2	33.4	5.6	-2.2
Eurasia	1	0.1	-0.1	1.2	0.1	0.1	1.3	0.1	0
Europe	1.8	0.1	-1.4	2.2	0.1	-0.6	2.3	0.1	-0.4
Middle East	2.8	0.1	-1.4	3.6	0.1	-0.6	3.9	0.1	-0.4
North America	7.5	2.3	-2.8	8.3	2.4	-0.6	8.1	2.6	-0.4
World Total	**484.1**	**260**	**-179.2**	**489.2**	**324.5**	**-91.6**	**472.9**	**340.5**	**-57.4**

Global abatement potential in paddy rice cultivation systems equates to approximately 27% - 35% of total annual net emissions. Marginal abatement cost (MAC) curve results are presented in Figure 2-2 for 2010, 2020, and 2030, assuming that production remains equal to baseline levels under the mitigation scenarios. Maximum abatement potential in the rice sector is 199 $MtCO_2e$ in 2010, 203 $MtCO_2e$ in 2020 and 200 $MtCO_2e$ in 2030.

Figure 2-2 also shows the finding that significant reductions are feasible even at a low values per ton of carbon. For example, there are approximately 76 $MtCO_2e$ of net GHG emission reductions that are cost-effective in 2010 at a price of $5/ton, (13.5 % of the baseline estimate). In 2030, approximately 87 $MtCO_2$ of reductions are feasible at a price of $5 per ton (11.5 % of the baseline estimate). These results suggest that there are significant opportunities for net GHG reductions in the rice cultivation sector.

Figure 2-2: Global Abatement Potential in Rice Cultivation with Production Equal to Baseline Levels: 2010, 2020, and 2030



The following section offers a brief description of CH_4 and N_2O emissions as well as changes in soil carbon stock from rice cultivation, and a discussion of projected trends in global baseline emissions. The subsequent section presents possible abatement technologies, their technical specifications, costs and potential benefits. The final section discusses the estimated abatement potential and MAC analysis at a regional level.

V.2.2 CH_4 and N_2O Emissions and Changes in Soil Carbon from Rice Cultivation

Rice production is a major source of GHG emissions. Global, Tier-I datasets such as EPA's Global Anthropogenic Non-CO_2 GHG Emissions Report (EPA, 2012) show that agriculture is the biggest source of CH_4 emissions, and within agriculture, rice cultivation is the second largest source, behind enteric fermentation.[1] Rice cultivation accounted for 7% of global CH_4 emissions in 2005 (USEPA, 2012). Rice cultivation is also a significant source of N_2O emissions but these are not included in most global datasets.

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[1] Global CH_4 emissions from agriculture were estimated at 3,035.4 $MtCO_2e$ (2005), about 45% of the global total of 6815.8 $MtCO_2e$. Rice produced 500.9 $MtCO_2e$ and enteric fermentation produced 1,894.3 $MtCO_2e$ (USEPA, 2012, Table 6).

In this section, we describe baseline emissions of CH_4,, N_2O, and soil carbon from rice cultivation as well as crop production data and assumptions that support the analysis of mitigation potential.

Rice production systems can be classified as wetland rice (irrigated, rain-fed and deepwater) or upland rice (Neue, 1993). Wetland rice is the largest category, and is responsible for large net CH_4 emissions.[2] Aerobic decomposition of organic matter gradually depletes the oxygen present in the soil and water, resulting in anaerobic conditions in the rice paddies. Methanogenic bacteria decompose soil organic matter under anaerobic conditions in rice paddies, generating CH_4. Significant amounts of CH_4 are oxidized by aerobic methanotrophic bacteria into CO_2 in the soil. The remaining unoxidized CH_4 is released to the atmosphere through diffusion and ebullition and through roots and stems of rice plants. Thus, unlike the non-paddy rice agricultural soils which are typically CH_4 sinks, paddy rice cultivation is a major source of CH_4 emissions.

N_2O is another significant component of net GHG emissions from rice cultivation. N_2O is produced through nitrification and denitrification from microbial activities under the anoxic condition. N_2O emissions occur directly from soils, and indirectly through volatilization of compounds such as NH_3 and NO_x and subsequent deposition as well as through leaching and runoff. Table 2-1 shows that in 2010, while CH_4 accounted for the largest share of emissions with 484.1 $MtCO_2e$ (65% of non-CO_2 emissions from rice cultivation), N_2O contributed substantially, with 260.0 $MtCO_2e$ (35%). Both dry and irrigated rice are a source of N_2O emissions.

Soil carbon stocks are not a non-CO_2 GHG but also have important implications for net GHG emissions and are affected by non-CO_2 mitigation options so we estimate total emissions net of their effect on soil C stocks in this report.

V.2.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

DNDC Modeling of GHG Fluxes and Crop Yields

The Denitrification-Decomposition (DNDC) model was used to simulate production, crop yields and greenhouse gas fluxes of global paddy rice under "business-as-usual" (BAU) condition and various mitigation strategies. DNDC is a soil biogeochemical model that simulates the processes determining the interactions among ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions, which collectively determine the rates of trace gas production and consumption in agricultural ecosystems (Li, 2001). Details of management (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the various biogeochemical processes (e.g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification, fermentation) embedded in DNDC (e.g., Li et al., 2004; Li et al., 2006; Li, 2011; Abdalla et al., 2011; Giltrap et al., 2011; Dai et al., 2012).[3]

DNDC predicts daily CH_4, N_2O and soil carbon fluxes from rice paddies through the growing and fallow seasons as fields remain flooded or move between flooded and drained conditions during the season.

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[2] Globally, about 2 percent of rice is grown in dry conditions and this production system is a net sink for CH_4 (source: DNDC estimates discussed below).

[3] The paddy-rice version of DNDC has been validated for a number of countries and world regions and is used for national trace gas inventory studies in North America, Europe, and Asia (e.g., Smith et al., 2002; Follador et al., 2011; Leip et al., 2011; Li et al., 2002; Cai et al., 2003; Li et al., 2005).

For this study, a modified version of the DNDC 9.5 Globe database was used to simulate crop yields and GHG fluxes from global paddy rice cultivation systems. The DNDC 9.5 global database contains information on soil characteristics, crop planted area, and management conditions (fertilization, irrigation, season, and tillage) on a 0.5 by 0.5 degree grid cell of the world. The database is used to establish the initial conditions in the model in 2000. The model considers all paddy rice production systems, including irrigated and rainfed rice, and single, double and mixed rice as well as deepwater and upland cropping systems. For this study, baseline and mitigation scenario modeling is carried out for all rice-producing countries in the world that produce a substantial quantity of rice.

The Food and Agriculture Organization (FAO) country-level statistics (FAOSTAT 2010) were used to establish harvested area for rice. The total area was calculated for each country in the Globe database for each type, and evenly distributed across all grid cells within a country in the absence of sub-national information. Figure 2-3 shows the distribution of rice across major systems for the five largest producers and an aggregate of the rest of the world.

Figure 2-3: DNDC Rice Cropland Area Sown, Top 5 countries, by Type and Water Management

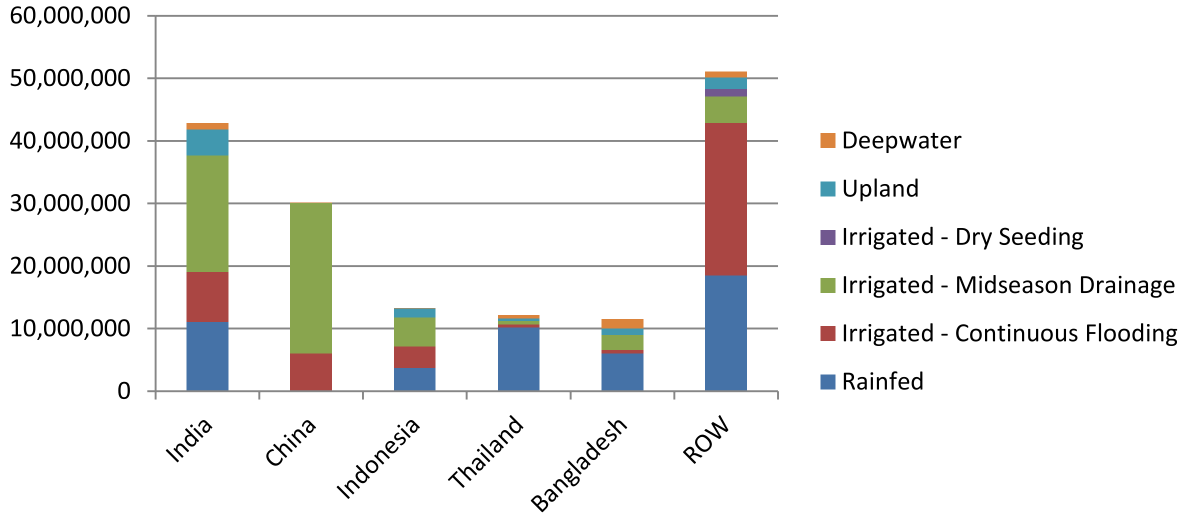

Table 2-2: Baseline yields for 2010, 2020 and 2030 for selected countries (kg/ha)

	2010				2020				2030			
Country/Region	Irrigated	Rainfed	Deepwater	Upland	Irrigated	Rainfed	Deepwater	Upland	Irrigated	Rainfed	Deepwater	Upland
Top 5 Countries by Production												
China	6,158.2	4,002.9	622.5	2,280.5	6,522.0	4,193.0	702.5	2,560.9	7,161.0	4,583.2	814.9	2,920.1
India	4,832.6	1,681.5	685.3	1,114.1	5,271.8	1,745.2	846.7	1,266.8	5,722.5	1,849.3	993.5	1,409.6
Indonesia	5,546.1	4,758.1	1,233.3	2,142.8	5,625.0	4,756.5	1,167.0	2,010.9	5,833.2	4,859.4	1,171.8	1,961.6
Bangladesh	7,322.9	4,823.1	1,257.6	2,501.9	7,447.9	4,732.3	1,592.3	2,927.3	7,642.4	4,766.4	1,857.9	3,196.2
Vietnam	7,388.0	5,208.4	963.2	2,240.9	7,503.2	5,156.1	940.4	2,386.4	7,647.7	5,222.3	960.5	2,513.0

Table 2-3: Baseline production for 2010, 2020 and 2030 for selected countries (metric tonnes)

	2010				2020				2030			
Country/ Region	Irrigated	Rainfed	Deepwater	Upland	Irrigated	Rainfed	Deepwater	Upland	Irrigated	Rainfed	Deepwater	Upland
Top 5 Countries by Production												
China	185,106,646	136,866	532	72,470	187,171,179	136,879	573	77,697	187,849,985	136,761	607	80,982
India	128,759,438	18,667,823	701,074	4,544,661	137,564,781	18,975,458	848,345	5,061,283	141,353,559	19,034,013	942,360	5,330,762
Indonesia	44,515,927	17,723,001	3,144	3,230,419	45,020,613	17,666,403	2,966	3,022,817	45,509,275	17,593,406	2,903	2,874,405
Bangladesh	22,123,824	29,082,198	1,870,274	2,471,779	22,891,662	29,029,646	2,409,109	2,942,311	23,309,923	29,015,593	2,789,425	3,187,968
Vietnam	27,265,526	15,725,436	260,980	1,121,298	27,967,786	15,723,459	257,362	1,206,084	28,142,533	15,722,150	259,495	1,253,843

The global meteorological data from the National Oceanic and Atmospheric Administration's National Centers for Environmental Prediction climate reanalysis product were used to establish climate data for 2010 in the model. The 2010 climate data were used for all model years. Planting and harvest dates were matched approximately to local growing season. Tillage and flooding and drainage dates for irrigated rice were established based on the planting dates.

Nitrogen fertilizer application rates were based on DNDC fertilizer use data, which is derived from global data sources. Table 2-4 summarizes the assumed fertilizer use per hectare for rice by country. Assumptions on the distribution of irrigated rice across water management regimes for each country were developed based on Yan et al. (2009) (see Table 2-5).

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type

Country	Planted Area	Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha)			
		Irrigated	Rainfed	Upland	Deepwater
Afghanistan	208,030	40	40	—	—
Angola	2,465	1	1	—	—
Argentina	211,148	90	90	9	—
Australia	175,085	180	180	15	—
Azerbaijan	5,720	20	20	1	—
Bangladesh	11,526,108	107	107	30	—
Belize	5,303	50	50	11	—
Benin	24,138	50	50	2	—
Bhutan	30,472	40	40	—	—
Bolivia	232,626	30	30	1	—
Brazil	2,696,270	50	50	15	—
Brunei	613	5	5	—	—
Bulgaria	24,732	60	60	24	—
Burkina-Faso	133,240	25	25	1	—
Burundi	18,582	40	40	—	—
Cambodia	2,730,963	30	30	—	—
Cameroon	32,568	35	35	1	—
Central-African-Republic	13,560	30	30	—	—
Chad	118,190	10	10	2	—
Chile	49,282	50	50	30	—
China	30,125,402	164	164	23	—
Colombia	435,924	108	108	18	—
Congo	520,829	2	2	—	—
Costa-Rica	87,372	50	50	18	—
Cote-dIvoire	493,322	7	7	2	—
Cuba	196,891	28	28	6	—

(continued)

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

Country	Planted Area	Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha)			
		Irrigated	Rainfed	Upland	Deepwater
Dominican-Republic	208,865	35	35	10	—
Ecuador	454,982	55	55	6	—
Egypt	402,249	203	203	34	—
El-Salvador	8,674	88	88	19	—
Ethiopia	40	25	25	3	—
France	18,919	127	127	28	—
French-Guiana	10,920	20	20	8	—
Gabon	202	35	35	—	—
Ghana	105,678	30	30	—	—
Greece	42,021	94	94	20	—
Guatemala	25,578	40	40	15	—
Guinea	818,010	1	1	—	—
Guinea-Bissau	162,054	30	30	1	—
Guyana	187,731	5	5	11	—
Haiti	82,387	10	10	2	—
Honduras	10,531	40	40	26	—
Hungary	53,797	35	35	15	—
India	42,848,326	69	69	20	—
Indonesia	13,261,499	82	82	16	—
Iran	563,918	79	79	17	—
Iraq	47,978	40	40	56	—
Italy	220,850	99	99	22	—
Japan	1,627,707	80	80	24	—
Kazakhstan	97,643	30	30	—	—
Kenya	7,358	50	50	8	—
Korea-North	582,246	70	70	15	—
Korea-South	902,339	189	189	34	—
Kyrgyzstan	14,724	39	39	5	—
Laos	848,955	45	45	2	—
Liberia	79,879	10	10	—	—
Madagascar	1,703,119	—	—	1	—
Malawi	28,106	20	20	9	—
Malaysia	677,984	65	65	16	—
Mali	646,334	40	40	2	—

(continued)

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

Country	Planted Area	Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha)			
		Irrigated	Rainfed	Upland	Deepwater
Mauritania	28,607	85	85	—	—
Mexico	162,208	85	85	18	—
Morocco	12,110	120	120	13	—
Mozambique	64,834	5	5	1	—
Myanmar	8,013,037	50	50	8	—
Nepal	1,455,906	22	22	5	—
Nicaragua	136,469	85	85	5	—
Niger	41,083	10	10	—	—
Nigeria	2,415,653	20	20	3	—
Pakistan	2,366,291	40	40	20	—
Panama	110,696	10	10	9	—
Paraguay	44,291	85	85	2	—
Peru	383,322	170	170	17	—
Philippines	4,355,767	60	60	19	—
Portugal	88,342	90	90	10	—
Romania	13,191	85	85	6	—
Russia	200,099	85	85	3	—
Rwanda	3,790	85	85	—	—
Senegal	75,558	85	85	4	—
Sierra-Leone	500,905	25	25	—	—
Spain	122,793	76	76	17	—
Sri-Lanka	1,062,007	60	60	16	—
Sudan	303	45	45	1	—
Suriname	39,758	50	50	27	—
Switzerland	2,320	40	40	27	—
Tajikistan	31,808	85	85	2	—
Tanzania	1,058,671	30	30	1	—
Thailand	12,116,749	30	30	20	—
The-Gambia	12,677	10	10	—	—
Togo	39,899	8	8	3	—
Trinidad-Tobago	2,838	35	35	21	—
Turkey	99,015	127	127	20	—
Turkmenistan	60,042	30	30	11	—
Uganda	54,966	30	30	—	—

(continued)

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

Country	Planted Area	Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha)			
		Irrigated	Rainfed	Upland	Deepwater
Ukraine	29,078	85	85	3	—
United-States	1,444,924	139	139	19	—
Uruguay	174,987	151	151	11	—
Uzbekistan	36,221	90	90	30	—
Venezuela	295,441	85	85	16	—
Vietnam	7,481,119	120	120	29	—
Zambia	13,872	12	12	4	—
Zimbabwe	176	15	15	8	—

Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%)

Region	Continuous Flooding	Midseason Drainage	Dry Seeding
Afghanistan	100%	0%	0%
Algeria	100%	0%	0%
Angola	100%	0%	0%
Argentina	100%	0%	0%
Australia	100%	0%	0%
Azerbaijan	100%	0%	0%
Bangladesh	20%	80%	0%
Belize	100%	0%	0%
Benin	100%	0%	0%
Bhutan	100%	0%	0%
Bolivia	100%	0%	0%
Brazil	100%	0%	0%
Brunei	100%	0%	0%
Bulgaria	100%	0%	0%
Burkina-Faso	100%	0%	0%
Burundi	100%	0%	0%
Cameroon	100%	0%	0%
Central-African-Republic	100%	0%	0%
Chad	100%	0%	0%
Chile	100%	0%	0%
China	20%	80%	0%
Colombia	100%	0%	0%
Comoros	100%	0%	0%

Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)

Region	Continuous Flooding	Midseason Drainage	Dry Seeding
Congo	100%	0%	0%
Costa-Rica	100%	0%	0%
Cote-dIvoire	100%	0%	0%
Cuba	100%	0%	0%
Dominican-Republic	100%	0%	0%
Ecuador	100%	0%	0%
Egypt	100%	0%	0%
El-Salvador	100%	0%	0%
Ethiopia	100%	0%	0%
Fiji	100%	0%	0%
France	100%	0%	0%
French-Guiana	100%	0%	0%
Gabon	100%	0%	0%
Ghana	100%	0%	0%
Greece	100%	0%	0%
Guatemala	100%	0%	0%
Guinea	100%	0%	0%
Guinea-Bissau	100%	0%	0%
Guyana	100%	0%	0%
Haiti	100%	0%	0%
Honduras	100%	0%	0%
Hungary	100%	0%	0%
India	30%	70%	0%
Indonesia	43%	57%	0%
Iran	100%	0%	0%
Iraq	100%	0%	0%
Italy	100%	0%	0%
Jamaica	100%	0%	0%
Japan	20%	80%	0%
Kazakhstan	100%	0%	0%
Kenya	100%	0%	0%
Korea-North	100%	0%	0%
Korea-South	100%	0%	0%
Kyrgyzstan	100%	0%	0%
Liberia	100%	0%	0%
Macedonia	100%	0%	0%

(continued)

Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)

Region	Continuous Flooding	Midseason Drainage	Dry Seeding
Madagascar	100%	0%	0%
Malawi	100%	0%	0%
Malaysia	100%	0%	0%
Mali	100%	0%	0%
Mauritania	100%	0%	0%
Mexico	100%	0%	0%
Micronesia	100%	0%	0%
monsoon Asia	43%	57%	0%
Morocco	100%	0%	0%
Mozambique	100%	0%	0%
Nepal	100%	0%	0%
Nicaragua	100%	0%	0%
Niger	100%	0%	0%
Nigeria	100%	0%	0%
Pakistan	100%	0%	0%
Panama	100%	0%	0%
Papua-New-Guinea	100%	0%	0%
Paraguay	100%	0%	0%
Peru	100%	0%	0%
Philippines	100%	0%	0%
Portugal	100%	0%	0%
Reunion	100%	0%	0%
Romania	100%	0%	0%
Russia	100%	0%	0%
Rwanda	100%	0%	0%
Senegal	100%	0%	0%
Sierra-Leone	100%	0%	0%
Solomon-Is	100%	0%	0%
Somalia	100%	0%	0%
South-Africa	100%	0%	0%
Spain	100%	0%	0%
Sri-Lanka	100%	0%	0%
Sudan	100%	0%	0%
Suriname	100%	0%	0%
Swaziland	100%	0%	0%
Tajikistan	100%	0%	0%

Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)

Region	Continuous Flooding	Midseason Drainage	Dry Seeding
Tanzania	100%	0%	0%
The-Gambia	100%	0%	0%
Timor-Leste	100%	0%	0%
Togo	100%	0%	0%
Trinidad-Tobago	100%	0%	0%
Turkey	100%	0%	0%
Turkmenistan	100%	0%	0%
Uganda	100%	0%	0%
Ukraine	100%	0%	0%
United-States-California	100%	0%	0%
United-States-Mid_South	0%	0%	100%
Uruguay	100%	0%	0%
Uzbekistan	100%	0%	0%
Venezuela	100%	0%	0%
Vietnam	100%	0%	0%
Zambia	100%	0%	0%
Zimbabwe	100%	0%	0%

Source: Yan et al. (2009).

A baseline scenario is established for each country using DNDC 9.5, reflecting assumptions on water management, fertilizer application, residue management and tillage practices described above. Rice yields and GHG fluxes (CH_4, direct and indirect N_2O and changes in soil organic carbon) were simulated in DNDC model for each grid cell and results were aggregated at the country level for irrigated, rainfed, deep water, and upland production systems for each scenario, in both mean annual rates per hectare and mean annual national totals.[4] Results were reported for 2010 and by 5-year increments through 2030.

Finally, results from DNDC were adjusted with projected acreage of these production systems by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. In DNDC, rice production areas were held constant at the 2010 level to obtain the biophysical effects of management practice changes on crop yields and GHG fluxes. Projected acreage changes from IMPACT model reflect socio-economic drivers (such as population growth) and technological changes to meet the global food demand (Nelson et al., 2010). The IMPACT modeling projects that while global rice production would increase by 11 percent between 2010 and 2030, the total area dedicated to rice cultivation would decrease by 5 percent during the same period due to productivity improvements.

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[4] The mean values were calculated using weighted averages; rice yields represent total annual yields of rice from all production systems.

V.2.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emission trends from global paddy rice cultivation and presents simulated baseline emissions projections.

Historical Emissions Estimates

According to the EPA Global Emissions Report (GER) (USEPA, 2012), total methane emissions from global rice cultivation increased by 4.4% between 1990 and 2005, from 480 $MtCO_2e$ to 501 $MtCO_2e$. Asia, the predominant rice-producing region, accounted for over 80% of the total CH_4 emissions in 2005. Africa contributed another 10%, and the remaining methane emissions in this sector came from Central and South America and other regions. The GER did not report historic N_2O emissions and soil carbon stock changes from the rice cultivation sector.

Projected Emissions Estimates

Worldwide CH_4 and N_2O emissions from rice cultivation are projected to have only modest increases between 2010 and 2030. This is mainly because demand for rice products will remain relatively constant while global food demand shifts towards more livestock and other more expensive food products with higher incomes. The estimated total CH_4 emissions from rice cultivation are 484.1 $MtCO_2e$ in 2010, 482.2 $MtCO_2e$ in 2020 and 472.9 $MtCO_2e$ in 2030. The total estimated N_2O emissions are 260.0 $MtCO_2e$ in 2010, 324.5 $MtCO_2e$ in 2020 and 340.5 $MtCO_2e$ in 2030.

V.2.3 Abatement Measures and Engineering Cost Analysis

The mitigation options included in the analysis were based on review of the literature to identify the most promising options, while also taking data availability and potential for modeling within DNDC into consideration. For the purposes of developing MAC curves for this study, mitigation options that increase net emissions of non-CO_2 GHG were excluded from the analysis.

Twenty-six mitigation scenarios were then analyzed using DNDC 9.5[5]. The scenarios addressed management techniques in various combinations hypothesized to reduce GHG emissions from rice systems: water management regime (continuous flooding, mid-season drainage, dry seeding, alternate wetting and drying, and switching to dryland rice production system), residue management (partial or total residue incorporation), tillage, and various fertilizer management alternatives (ammonium sulfate in place of urea, urea with nitrification inhibitor, slow release urea, 10% reduced fertilizer, 20% reduced fertilizer, and 30% reduced fertilizer).

The water management system under which rice is produced is one of the most important factors influencing CH_4 emissions. Specifically, switching from continuous flooding of rice paddy fields to draining flooded fields periodically during the growing season – a water conservation practice that is increasingly adopted in the baseline to reduce water use – would significantly reduce CH_4 emissions. Other practices (e.g., fertilizer applications, tillage practices and residue management) also alter the soil conditions and hence affect crop yields and the soil carbon- and nitrogen-driving processes such as

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[5] Note that 38 different scenario names are reported in the outputs. Because water management practices are assumed not to affect non-irrigated rice emissions, the simulation results for options combine d with continuous flooding or midseason drainage are the same for non-irrigated rice. The analogous options that alter fertilizer and other management practices but do not affect water management were identified as beginning with “base” rather than “cf” or “md”.

decomposition, nitrification and denitrification (Neue and Sass, 1994; Li et al., 2006). Due to the complex interactions, changes in management practices would trigger changes in multiple GHG fluxes. For instance, while drainage of rice fields during the growing season would significantly reduce CH_4 emissions, emissions of N_2O actually increase (Zheng et al., 1997, 2000; Cai et al., 1999; Zou et al. 2007).

Rice mitigation options

The mitigation options included for rice water management system under which rice is produced is one of the most important factors influencing CH_4 emissions. Specifically, switching from continuous flooding of rice paddy fields to draining flooded fields periodically during the growing season – a water conservation practice that is increasingly adopted in the baseline to reduce water use – would significantly reduce CH_4 emissions. Other practices (e.g., fertilizer applications, tillage practices and residue management) also alter the soil conditions and hence affect crop yields and soil carbon- and nitrogen-driving processes.

There were 26 scenarios that were run using DNDC 9.5 (see Table 2-6). The scenarios addressed management techniques in various combinations hypothesized to reduce GHG emissions from rice systems: flood regime (continuous flooding [CF], mid-season drainage [MD], dry seeding [DS], alternate wetting and drying [AWD], and switching to dryland (upland) rice), residue management (partial removal or 100% incorporation), conventional tillage or no till, and various fertilizer alternatives (conventional / urea, ammonium sulfate in place of urea, urea with nitrification inhibitor, slow release urea, 10% reduced fertilizer, 20% reduced fertilizer, 30% reduced fertilizer, and DNDC optimization of fertilizer application to maximize yields). Further definition of these assumptions is provided in Table 2-7.

Table 2-6: Alternative Rice Management Scenarios Simulated using DNDC

Abbreviation	Scenario	Flooding	Residue Incorporation	Alternative Management	Fertilization
cf_r50	Continuous Flooding	CF	50%	—	conventional
cf_r100	Continuous Flooding, 100% Residue Incorporation	CF	100%	—	conventional
cf_r50_amsu	Continuous Flooding, Ammonium Sulphate Fertilizer	CF	50%	—	ammonium sulfate
cf_r50_ninhib	Continuous Flooding, Nitrification Inhibitor Fertilizer	CF	50%	—	nitrification inhibitor
cf_r50_slowrel	Continuous Flooding, Slow Release Fertilizer	CF	50%	—	slow release
cf_r50_notill	Continuous Flooding, No Till	CF	50%	no till	conventional
cf_r50_f70	Continuous Flooding, 30% Reduced Fertilizer	CF	50%	—	30% reduced
cf_r50_f90	Continuous Flooding, 10% Reduced Fertilizer	CF	50%	—	10% reduced
cf_r50_auto	Continuous Flooding, Auto-fertilization to maximize yields	CF	50%	—	Automatically adjusted by DNDC to maximize yields
md_r50	Mid-season Drainage	MD	50%	—	conventional

(continued)

Table 2-6: Alternative Rice Management Scenarios Simulated using DNDC (continued)

Abbreviation	Scenario	Flooding	Residue Incorporation	Alternative Management	Fertilization
md_r100	Mid-season Drainage w/100% Residue Incorporation	MD	100%	—	conventional
md_r50_amsu	Mid-season Drainage, Ammonium Sulphate Fertilizer	MD	50%	—	ammonium sulfate
md_r50_ninhib	Mid-season Drainage, Nitrification Inhibitor Fertilizer	MD	50%	—	nitrification inhibitor
md_r50_slowrel	Mid-season Drainage, Slow Release Fertilizer	MD	50%	—	slow release
md_r50_notill	Mid-season Drainage, No Till	MD	50%	no till	conventional
md_r50_f70	Mid-season Drainage, 30% Reduced Fertilizer	MD	50%	—	30% reduced
md_r50_f90	Mid-season Drainage, 10% Reduced Fertilizer	MD	50%	—	10% reduced
md_r50_ds	Mid-season Drainage, Dry Seeding	MD w/DS	50%	—	conventional
md_r50_auto	Mid-season Drainage, Auto-fertilization to maximize yields	MD	50%	—	Automatically adjusted by DNDC to maximize yields
awd_r50	Alternate Wetting & Drying (AWD)	AWD	50%	—	conventional
awd_r50_ninhib	AWD w/Nitrification Inhibitor	AWD	50%	—	nitrification inhibitor
awd_r50_slowrel	AWD w/Slow Release	AWD	50%	—	slow release
base_r50_ds	Dry Seeding	DS	50%	—	conventional
base_r50_f80_ds	Dry Seeding, 20% Reduced Fertilizer	DS	50%	—	20% reduced
dry_r50	Dryland Rice	dryland rice	50%	—	conventional
dry_r50_f80	Dryland Rice, 20% Reduced Fertilizer	dryland rice	50%	—	20% reduced

For non-irrigated rice, there is no difference between scenarios with alternative water management. Thus, we refer to those scenarios for the non-irrigated rice with “base_” in front rather than “cf” or “md”.

Table 2-7: Rice Management Techniques

Management Technique	Description
Rice flooding	
Continuous Flooding (CF)	rice paddy is flooded on planting date and drained 10 days prior to harvest date - applies to both irrigated and rainfed rice
Mid-season drainage (MD)	rice paddy is drained twice during growing season for 8 days - final drainage is 10 days prior to harvest date - applies only to irrigated rice
Alternate wetting and drying (AWD)	rice paddy is initially flooded to 10 cm – water level is reduced at rate of -0.5 cm/day till to -5cm and then reflooded at rate of 0.5 cm/day till to 10 cm - applies only to irrigated rice
Dryland rice	all irrigated and rainfed rice are swapped for dryland rice - no flooding occurs
Rice seeding	
Direct seeding (DS)	rice paddy is flooded 40 days after planting date and drained 10 days prior to harvest date - applies to both irrigated and rainfed rice
Residue incorporation	
50%	50% of above-ground crop residue is removed - remaining residue is incorporated at next tillage
100%	all residue remains in place and is incorporated at next tillage
Tillage	
Conventional	prior to first crop in rotation tillage to 20cm depth; subsequent tillages (following each crop in rotation) to 10cm depth
No-till	tillage only mulches residue
Fertilizer	
Conventional	fertilizer N applied as urea on plant date using a crop-specific rate
Ammonium sulfate	fertilizer N applied as ammonium sulfate on plant date using a crop-specific rate
Nitrification inhibitor	nitrification inhibitor is used with urea; reduced conversion of NH4 to NO3 is simulated with 60% efficiency over 120 days
Slow-release	slow-release urea applied on planting date – N is released over 90 days at a linear rate
10% reduced	Crop-specified baseline fertilizer N rate is reduced by 10% (applied as urea)
20% reduced	Crop-specified baseline fertilizer N rate is reduced by 20% (applied as urea)
30% reduced	Crop-specified baseline fertilizer N rate is reduced by 30% (applied as urea)
auto fertilization	Fertilizer N is applied at the rate that maximizes crop yield

Most of the major rice producing countries have some mix of flood regimes in DNDC (see Table 2-5). To determine baseline emissions for each country, simulation results were combined based on the fraction of rice area in each rice category (deepwater, upland, rainfed, and irrigated) and flood regime for irrigated rice. For instance, baseline emissions for Bangladesh were determined by averaging the results of the CF and MD scenarios with 50% residue removal (cf_r50 * 0.2 + md_r50 * 0.8).

However, for the purposes of calculating emissions reductions, mitigation options were compared to the portions of the baseline to which they could potentially be applied rather than to the national weighted average. For instance, application of the mitigation option of switching to ammonium sulphate fertilizer (cf_r50_amsu) was compared to baseline emissions from continuously flooded rice with conventional fertilizer (cf_r50) and to baseline emissions from rice managed using mid-season drainage with conventional fertilizer (md_r50) rather than being compared to the baseline weighted average emissions per ha. This is done to better represent the mitigation potential from adopting each mitigation option on each baseline subcategory. As an example, an option such as cf_r50_amsu may result in emissions reductions relative to cf_r50 but increases in emissions relative to md_r50 (and possibly the weighted baseline emissions as well) in many countries. This is resulting from the change in water management regime in moving from mid-season drainage to continuous flooding, whereas we are trying to isolate the effects of changing fertilizer for a given baseline water management strategy in that example.

- **Capital Cost:** None of the options were assumed to have any capital cost.
- **Annual Operation and Maintenance (O&M) Cost:** Changes in labor, fertilizer, and other inputs associated with each option.
- **Annual Benefits:** Calculated based on changes in production associated with changes in yield, valued at market prices.
- **Applicability:** All options applicable for a given cropping pattern were assumed available to all acres in all countries. However, water management options (e.g., shifting from continuous flooding to midseason drainage, etc.) are only applicable to irrigated systems. No water management options are available for rainfed, deepwater, or upland rice
- **Technical Efficiency:** Determined by the DNDC Model for each country, production type, and water management combination for each mitigation option.
- **Technical Lifetime:** Indefinite; there are no capital costs being included for which a lifetime must be defined.

V.2.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-CO_2 sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

V.2.4.1 MAC Analysis Results

The MAC analysis of the mitigation options described above suggests that net GHG abatement potential for global paddy rice cultivation equates to approximately 6 percent of its total annual emissions between 2010 and 2030 at a carbon price of $5 per ton of CO_2 equivalent ($/t$CO_2$e). In 2030, total abatement potential in the sector is 21 MtCO_2e at no carbon price, 57 MtCO_2e at a carbon price of $5/t$CO_2$e, and 124 Mt$CO_2$e at a carbon price of $20/t$CO_2$e, representing 2%, 6% and 12% of the net GHG emissions in the year, respectively. Figure 2-4 presents the MAC curves for the global rice cultivation, in 2010, 2020 and 2030. The estimated net GHG mitigation potential at various break-even prices for the top-emitting countries and aggregate regions comprising the rest of the globe are presented in Table 2-8.

Table 2-8: Abatement Potential by Region at Selected Break-Even Prices in 2030 (MtCO_2e)

Country/ Region	Break-Even Price ($/t$CO_2$e)										
	–10	–5	0	5	10	15	20	30	50	100	100+
Top 5 Emitting Countries											
India	2.4	2.4	5.5	14.5	15.1	16.8	16.8	16.8	20.4	28.8	34.5
Indonesia	6.0	9.1	12.8	14.4	16.3	19.1	19.1	19.1	21.8	24.8	25.6
Bangladesh	2.8	3.4	19.5	30.4	30.4	30.5	30.5	31.9	33.1	35.6	35.9
Vietnam	0.0	0.0	6.9	9.0	9.8	13.2	16.0	16.0	16.0	17.6	21.6
China	0.6	1.6	3.2	3.5	9.5	10.0	10.6	10.6	12.6	19.1	23.7
Rest of Region											
Africa	0.1	0.3	0.8	1.2	1.6	2.7	3.6	4.1	5.1	5.4	5.7
Asia	2.1	2.7	6.9	9.2	14.7	16.6	21.1	25.5	28.2	31.3	34.9
Central & South America	0.4	0.6	1.4	3.5	4.5	6.3	7.3	8.1	9.5	10.9	12.1
Eurasia	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.4
Europe	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.7	1.0
Middle East	0.0	0.1	0.1	0.1	0.3	0.3	0.4	0.5	0.8	1.1	1.2
North America	0.7	0.7	0.8	1.0	1.5	1.7	1.9	2.2	2.8	3.4	3.7
World Total	**15.2**	**20.9**	**57.8**	**87.0**	**103.9**	**117.5**	**127.8**	**135.4**	**150.9**	**178.9**	**200.3**

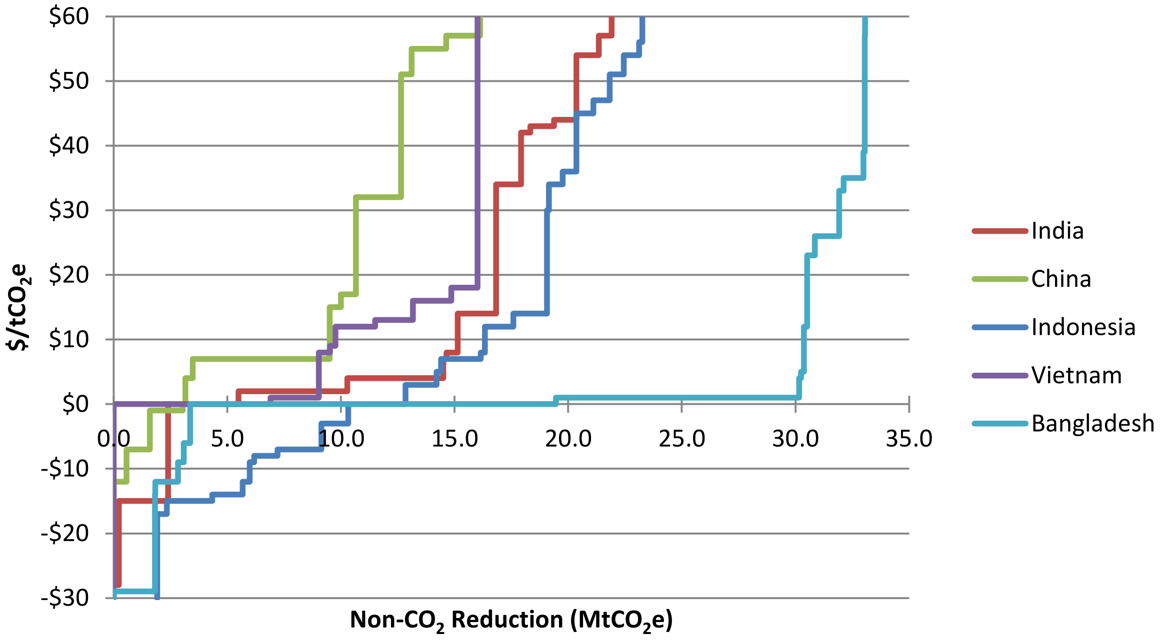
Mitigation potential and its cost-effectiveness vary significantly by country or region. At the regional level, Asia (in particular South and Southeast Asia), Africa, Central and South America and the European Union show the most significant potential for reducing GHG emissions from rice cultivation. For instance, in 2030 mitigation potential in Asia is estimated to be 27 MtCO_2e with no carbon price and 34 MtCO_2e at a carbon price of $20/t$CO_2$e. Central and South America can achieve mitigation potential of 12 MtCO_2e in 2030 at no carbon price, and mitigation potential can increase to 22 MtCO_2e at a carbon price of $20/t$CO_2$e. Figure 2-4 shows the MAC curves for the top-five emitting countries in 2030.

There are a large number of mitigation options included for rice cultivation and almost all provide net GHG reductions. The overall distribution of GHG mitigation across mitigation options included in this analysis is presented in Table 2-9. The options providing the largest quantify of GHG reductions are the two that involve switching to dryland production, which significantly reduces or eliminates CH_4 emissions. Those options do result in major reductions in yields, however. Other options that account for large reductions include nitrification inhibitors in combination with midseason drainage or alternate wetting and drying, along with switching to no-till, fertilizer reductions, and optimal fertilization options on non-irrigated lands. The relative share of mitigation provided by different options varies across years due to the dynamics of GHG emissions, especially for changes in soil C.

Table 2-9: Distribution of Net GHG Reductions across Mitigation Options, Baseline Production Case

	2010	2020	2030
base_r100	1.74	0.35	0.36
base_r50_amsu	2.23	1.86	1.57
base_r50_ninhib	4.86	4.38	4.64
base_r50_slowrel	1.37	0.36	0.27
base_r50_notill	4.42	15.39	17.84
base_r50_f70	6.59	12.77	13.12
base_r50_f80	4.49	8.81	8.96
base_r50_f90	2.30	4.52	4.57
base_r50_auto	5.89	10.55	11.46
base_r50_ds	0.95	0.61	0.57
base_r50_f80_ds	1.01	0.66	0.62
cf_r100	0.11	0.00	0.00
cf_r50_amsu	1.26	1.50	1.51
cf_r50_ninhib	2.22	2.57	2.61
cf_r50_slowrel	2.24	1.96	1.87
cf_r50_notill	0.04	0.01	0.01
cf_r50_f70	0.46	0.47	0.46
cf_r50_f80	0.34	0.35	0.35
cf_r50_f90	0.19	0.19	0.19
cf_r50_auto	0.40	0.23	0.18
md_r50	5.08	5.52	5.59
md_r100	6.36	3.76	3.75
md_r50_amsu	6.47	6.97	6.92
md_r50_ninhib	18.32	20.02	20.40
md_r50_slowrel	7.93	7.43	7.48
md_r50_notill	3.12	3.10	2.93
md_r50_f70	6.14	6.66	7.07
md_r50_f80	5.98	6.49	6.80
md_r50_f90	5.61	6.10	6.30
md_r50_auto	4.80	5.13	5.33
md_r50_ds	1.34	1.01	1.01
awd_r50	5.27	4.85	4.31
awd_r50_ninhib	19.70	19.11	17.95
awd_r50_slowrel	8.41	7.53	7.08
dry_r50	25.35	15.00	13.23
dry_r50_f80	25.74	17.00	13.00
TOTAL	**198.73**	**203.23**	**200.33**

Figure 2-4: Marginal Abatement Cost Curve for Top 5 Emitters in 2030, Baseline Production Case



V.2.5 Sensitivity Analyses

In this section, we explore sensitivity analyses to examine the potential effects of alternative assumptions on estimated mitigation potential. Because many of the mitigation options simulated impact rice yields, the assumption of constant production implies a change in the area devoted to rice production. There are options that increase productivity, but also many that decrease productivity. Thus, land requirements may increase or decrease to maintain production at baseline levels, but overall the package of mitigation options being considered tends to reduce yields. In this sensitivity analysis, we hold the area of cultivated rice at the baseline area and recalculate the MACs.

Baseline Acreage

This section explores this relationship further by presenting an alternative scenario built around a constraint on the number of acres, keeping the harvested area the same as estimated in the baseline.

As before, the MAC model only includes options that result in lower emissions. The result for area held fixed at projected baseline area is shown in Figure 2-5. Generally speaking, emissions and emission reduction potential are slightly higher although the effects vary by country. Overall, global maximum potential mitigation is 320 MtCO2e, 60% higher than the global maximum potential mitigation of 200MtCO2e in the constant production case. Figure 2-6 shows the MAC for the top 5 rice producing countries under the constant area case. China's MAC shows relatively little change under the assumption of constant area, but the other countries show increased emissions mitigation potential to varying degrees.

Figure 2-5: Marginal Abatement Cost Curve, Baseline Area Case

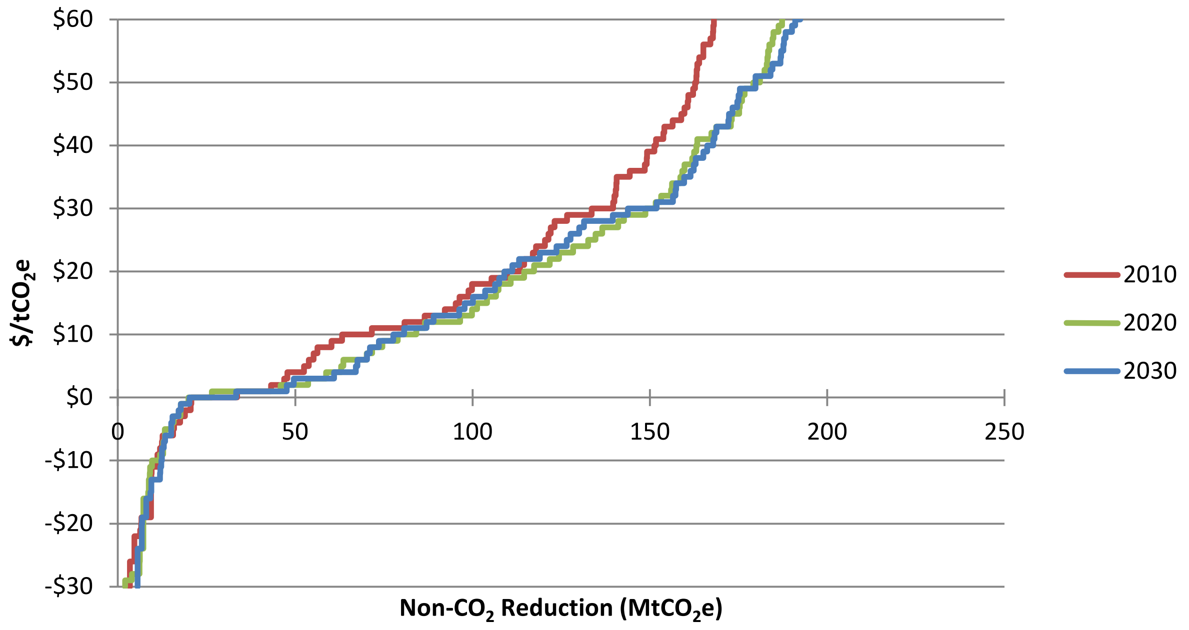
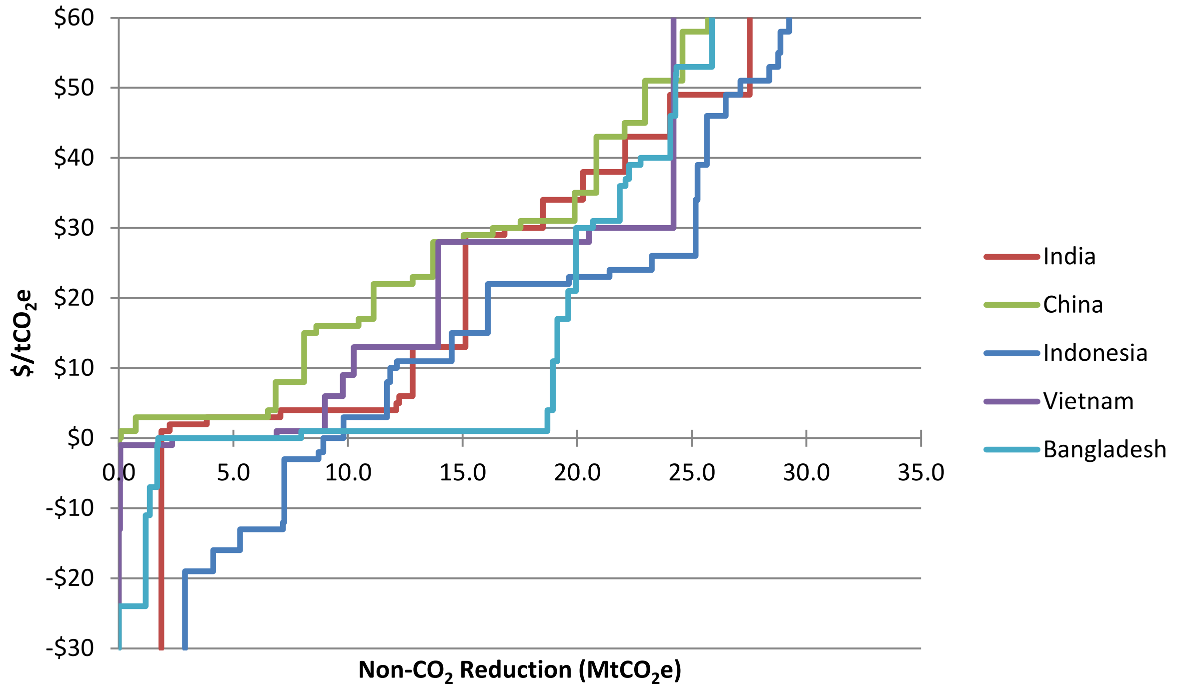


Figure 2-6: Marginal Abatement Cost Curve for Top 5 Emitters in 2030, Baseline Area Case



V.2.5. Uncertainties and Limitations

Given the complexities of the global rice sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Availability and quality of data to represent the highly complex and heterogeneous rice production systems of the world.*** Although there are major improvements in representing the global rice production systems and the business-as-usual baseline conditions compared to the previous EPA report (USEPA, 2006), data in some areas, such as management practices, are not always available for all countries or regions and approximations must be made based on limited literature or expert judgment. Moreover, collecting and developing consistent cost estimates of emerging and/or not widely adopted mitigation measures is challenging.
- ***Biophysical modeling uncertainties, in particular with respect to soil organic carbon simulations.*** The DNDC modeling of the business-as-usual baseline conditions and mitigation scenarios was performed using a set of inputs and assumptions developed based on various sources. The quality of input data ultimately affects the simulated results. Soil organic carbon, which has a significant impact on the net GHG emissions from the sector, is particularly challenging to simulate given the lack of monitoring data at the global scale. Sensitivity tests would be useful to assess how alternative modeling approaches and assumptions may influence modeling results.
- ***Optimistic assumptions on technology adoption.*** The analysis assumes that if mitigation technology is considered feasible in a country or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially slow the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.
- ***Potential interactions of multiple mitigation measures are not fully addressed in this analysis.*** In this analysis, mitigation options are applied to independent segments of the rice production systems to avoid double counting. In reality, multiple mitigation options can be applied, and their order of adoption and potential interactions may affect the aggregate GHG mitigation

References

Bates, J., N. Brophy, M. Harfoot and J. Webb. (2009). Agriculture: methane and nitrous oxide. Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC). pp. 62.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You. (2010). Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. International Food Policy Research Institute: Washington, DC.

Neue, H. 1993. Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming. *BioScience* 43 (7): 466-73.

U.S. Environmental Protection Agency (USEPA) (2006). Global Mitigation of Non-CO2 Greenhouse Gases. EPA 430-R-06-005. Washington DC.

USEPA (2012). Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 – 2030. EPA 430-D-11-003. Washington DC.

World Resources Insititute (WRI). (2012). Climate Analysis Indicators Tool (CAIT) database. Available at http://www.wri.org/project/cait/.

V.3. Livestock

V.3.1 Sector Summary

Livestock operations generate methane (CH_4) and nitrous oxide (N_2O) emissions. The greenhouse gas (GHG) emissions mainly come from two sources, enteric fermentation and manure management. Methane is produced as a by-product of the digestive process in animals through a microbial fermentation process. The quantity of enteric fermentation CH_4 emissions is determined by the animal's digestive system, diet and management practices. Livestock manure management can produce both CH_4 and N_2O emissions. Methane is produced when manure decomposes under anaerobic conditions. The quantity of manure CH_4 emissions is determined by the type of treatment or storage facility, the ambient climate, and the composition of the manure. Manure N_2O emissions result from nitrification and denitrification of the nitrogen that is excreted in manure and urine.

In 2010, the global non-CO_2 GHG emissions from livestock operations were approximately 2,286 $MtCO_2e$. Figure 3-1 presents projected total emissions for the top 5 emitting countries and the total for the rest of the world.

Methane emissions predominate with 2,152 $MtCO_2e$ emitted in 2010. Globally, livestock is the largest source of CH_4 emissions, contributing approximately 29% of total global CH_4 emissions in 2010. As shown in Figure 3-2, the top 5 emitting countries – India, China, Brazil, the United States, and Pakistan – accounted for 44% of the sector's total CH_4 emissions. Growth in CH_4 emissions is expected to be about 20% between 2010 and 2030.

Figure 3-1: Total Net GHG Emissions and Projections for the Livestock Sector: 2000-2030

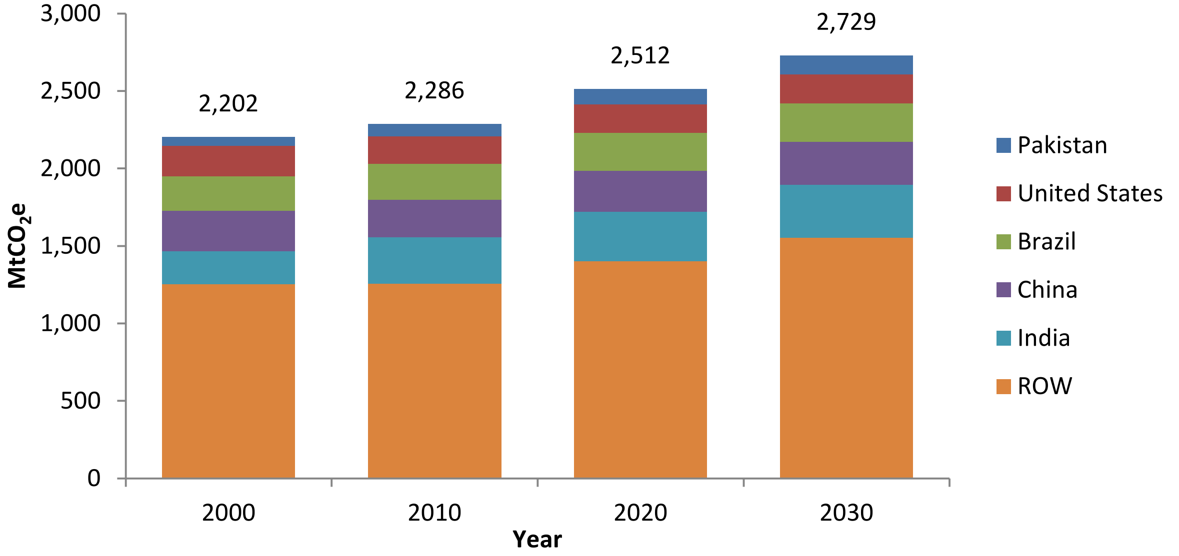
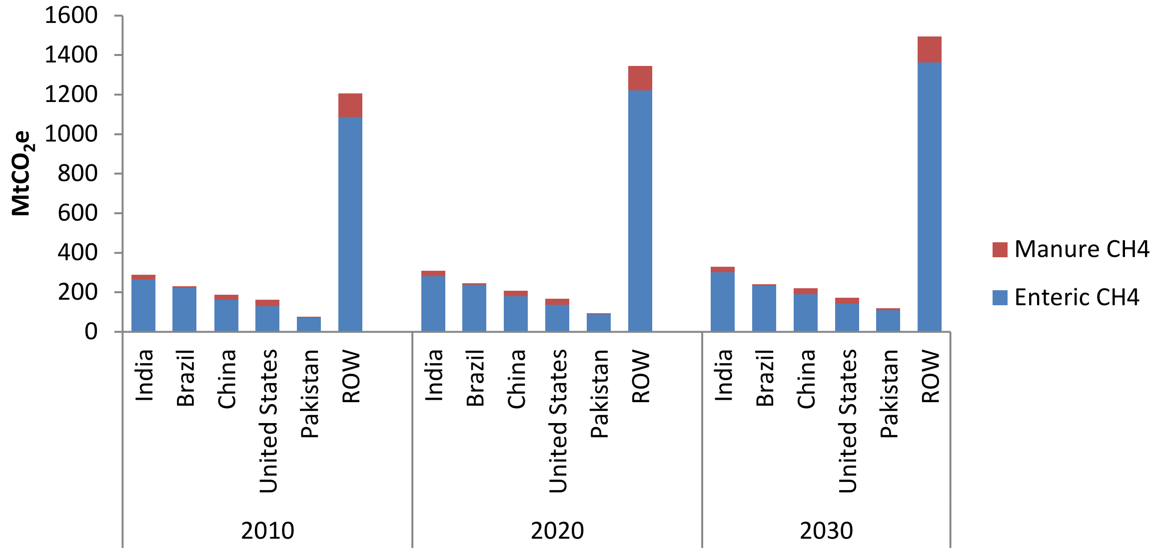
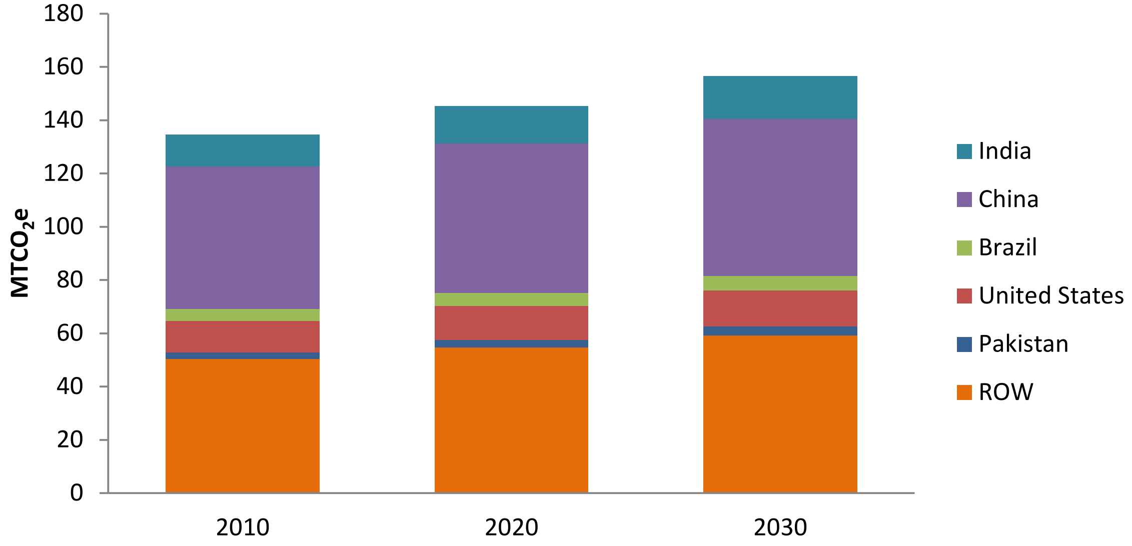


Figure 3-2: CH_4 Emissions Projections for the Livestock Sector: 2010–2030



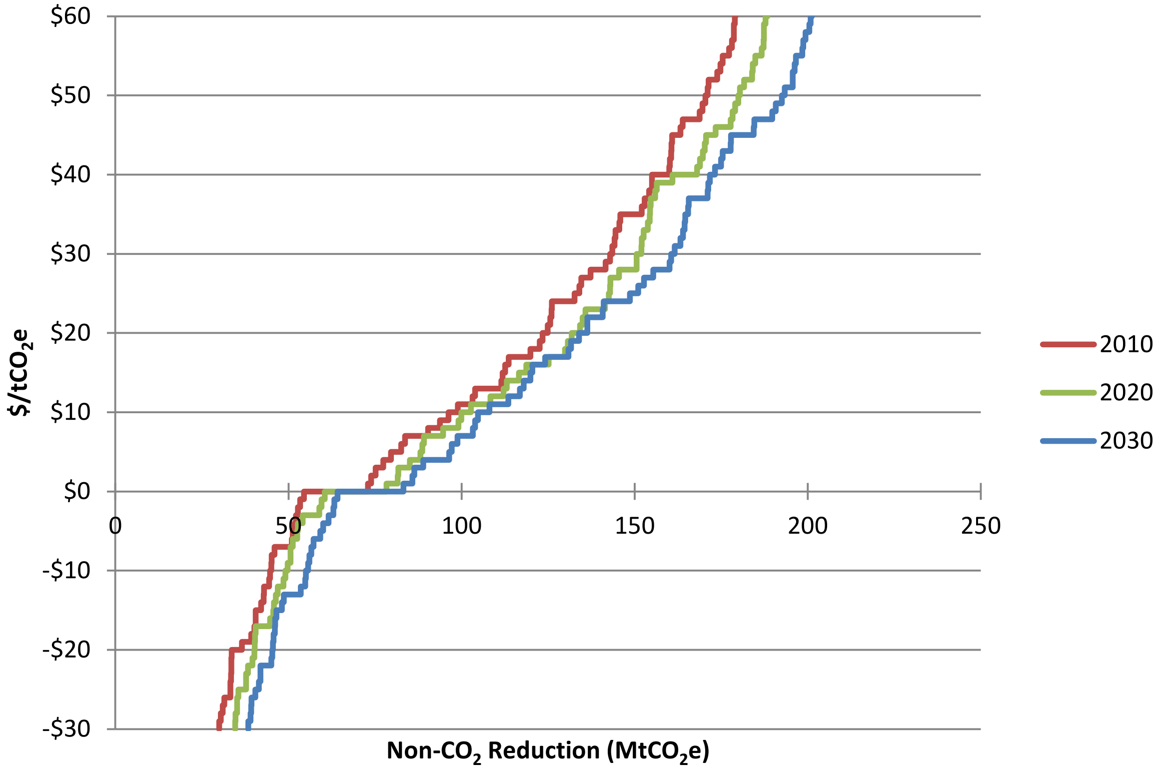
Nitrous oxide emissions from manure management are a second significant source of GHG emissions within the livestock sector, contributing an additional 135 $MtCO_2e$. Livestock contributed approximately 4% of total global N_2O emissions in 2010. As presented in Figure 3-3, China, India, the United States, Brazil, and Pakistan together account for 63% of global N_2O emissions from livestock operations in 2010. N_20 emissions are expected to grow about 16% between 2010 and 2030 to about 156 $MtCO_2e$, slightly lower than the projected growth in CH_4 emissions over the same time period.

Figure 3-3: N_20 Emissions Projections from the Livestock Sector: 2010–2030



Marginal abatement cost (MAC) curve results assuming the production of livestock products remains constant at projected baseline levels are presented in Figure 3-4. Maximum abatement potential in the livestock sector is 268 $MtCO_2e$ in 2030, or about 9.8% of total GHG emissions in that year.[1] These results suggest that there are significant opportunities for GHG reductions in the livestock sector. Approximately 86 $MtCO_2e$ can be reduced in 2030 at no or low carbon prices below $5 per ton of CO_2 equivalent.

Figure 3-4: Global Abatement Potential in Livestock Management: 2010, 2020, and 2030



The following section offers a brief description of CH_4 and N_2O emissions from livestock operations, and a discussion of projected trends in global baseline emissions. The subsequent section presents possible abatement technologies, their technical specifications, costs and potential benefits. The final section discusses the MAC analysis and estimated abatement potential at global and regional levels.

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[1] This analysis only assesses abatement measures that are designed to reduce CH_4 emissions. Mitigation options that focus on potential reductions in N_2O emissions are not included due to relatively small potential abatement potential and limited information on abatement measures and costs. However, N_2O emissions are affected by changes in livestock productivity under our primary scenario with production held constant because the number of animals required to produce a given quantity of livestock products, and their associated emissions, changes with productivity.

V.3.2 CH_4 and N_2O Emissions from Livestock Management

This section discusses how CH_4 and N_2O emissions are produced in livestock operations and the current projections of baseline emissions between 2010 and 2030.

V.3.2.1 CH4 Emissions from Enteric Fermentation

Enteric fermentation produced about 1945 $MtCO_2e$ of CH_4 in 2010 and accounts for about 90% of the total CH_4 emissions from livestock. Methane is produced as a by-product of the digestive process in animals. This microbial fermentation process produces CH_4 that can be exhaled or excreted by the animal. The quantity of CH_4 produced through enteric fermentation depends largely on the animal's digestive system, diet and management practices. Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major sources of enteric CH_4 emissions; nonruminant animals (e.g., swine, horses, mules) also produce enteric CH_4 emissions but at much lower rates compared to ruminant animals.

The quantity, quality and digestibility of feed significantly affect enteric CH_4 emissions. The main constituents of the diet - sugars, starch, fiber, protein and lipid - appear to have varying impacts on methane emissions. In general, increased intake of starch and soluble sugars decreases rumen pH, which suppresses methanogens, thus resulting in lower CH_4 emissions. Lower feed quality such as higher content of insoluble fiber leads to higher CH_4 emissions. Provision of feed supplements, such as dietary oils, is found to have an inhibitory effect on CH_4 production in the rumen (Hristov et al., 2013). Management practices that improve animal productivity, such as the usage of antibiotics and bovine somatotropin (bST), often reduce CH_4 emissions per unit of meat or milk even though these activities can increase CH_4 emissions per animal.

V.3.2.2 CH_4 and N_2O Emissions from Manure Management

Manure Management CH_4 Emissions

Manure management produced about 206 $MtCO_2e$ of CH_4 in 2010, smaller than enteric fermentation but still a significant global source of CH_4 at about 3% of global total methane production.[2] In livestock waste management systems, CH_4 is produced when manure decomposes under anaerobic conditions, for example in lagoons, ponds or pits. The quantity of CH_4 emitted from manure management operations is determined by the type of treatment or storage facility, the ambient climate, and the composition of the manure (USEPA, 2012). Higher ambient temperature and moisture conditions favor CH_4 production.

Manure Management N_2O Emissions

In addition to CH_4, livestock waste management produced about 135 $MtCO_2e$ of N_2O in 2010. Nitrous oxide is produced from livestock waste through nitrification and denitrification. Nitrous oxide emissions from livestock waste depend on the composition of the waste, the type of bacteria involved in the decomposition process, and the oxygen and liquid content of waste (USEPA 2012). Nitrous oxide generation is most likely to occur in dry manure handling systems.

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[2] Global CH4 emissions in 2010 totaled 7,549.2 MTCO2e (USEPA, 2012, Table A2)

V.3.2.3 Baseline CH_4 and N_2O Emissions Estimates

This section discusses the historical and projected baseline emissions for the livestock sector. Historical emissions are characterized as those released between 1990 and 2005. Projected emissions cover the 20-year period 2010 – 2030.[3]

Historical Emissions Estimates

Over the 1990 – 2005 period, total non-CO_2 GHG emissions from livestock operations increased by 4% between 1990 and 2005, from 2,201 to 2,292 $MtCO_2e$ (USEPA, 2012). This modest growth is caused by two opposing trends: growth in Africa and Central and South America has been partially offset by the effects of market restructuring in non-OECD Europe. Enteric fermentation CH_4 emissions increased 7% between 1990 and 2005 while emissions of CH_4 and N_20 from livestock waste management decreased 9% between 1990 and 2005.

Projected Emissions Estimates

This analysis uses the 2005 country-level livestock population data from the Global Anthropogenic Non-CO_2 Emissions Report ("GER") as a starting point (USEPA, 2012). However, for the period 2010—2030 an alternate business-as-usual forecast was constructed using livestock production and market price projections generated by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Nelson et al., 2010) to derive projected livestock populations. A key rationale for relying directly on these model outputs is that the IFPRI IMPACT model projections provide a set of prices and global production patterns consistent with their livestock population and productivity assumptions. Using these data improves the internal consistency of the MAC analysis.[4]

Table 3-1 shows projected baseline emissions from livestock management for the top 5 emitting countries and the rest of the world, divided into major regions.[5] Global emissions from livestock management are projected to grow at an average annual rate of 0.9%. In general, emissions are growing much more rapidly in developing countries than in the developed world.

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[3] The year 2010, although historical, is the first year of the modeling forecast period.

[4] The IMPACT outputs separated the world into 116 regions, with larger countries defined individually and smaller countries combined into regions. A mapping was created between IMPACT regions and the 195 countries in this analysis, using shares of country-level livestock population in 2010 based on USEPA (2012) to disaggregate regional projections from the IMPACT model to individual countries within each region.

[5] Regional totals exclude the top 5 emitting countries that are presented separately in the table.

Table 3-1: Projected Baseline Emissions from Livestock Management: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
India	300	311	322	333	344	0.7%
China	242	253	262	271	278	0.7%
Brazil	235	247	248	247	246	0.2%
United States	174	179	181	184	186	0.3%
Pakistan	80	89	99	110	122	2.1%
Rest of Regions						
Asia	259	283	307	335	367	1.8%
Africa	293	320	343	369	395	1.5%
Europe	257	257	257	257	257	0.0%
Middle East	28	30	32	35	38	1.6%
Central & South America	227	245	258	271	284	1.1%
Eurasia	118	120	121	124	126	0.3%
North America	74	77	80	83	85	0.8%
World Totals	**2,286**	**2,411**	**2,512**	**2,619**	**2,729**	**0.9%**

Table 3-2 summarizes projected baseline emissions from enteric fermentation. Worldwide CH_4 emissions from enteric fermentation are projected to increase at an average annual rate of 0.9% between 2010 and 2030. The top five countries, India, Brazil, China, the United States, and Pakistan, combine for about 44% of global totals in 2010, but the baseline projection has emissions from all of these countries except Pakistan growing at a slower rate than the global average. Annualized growth rates in the top five countries average 0.7%, lower than the average 0.9% growth projected in the rest of regions. By 2030, the top five countries are the source of 42% of global enteric fermentation emissions.

Table 3-2: Projected Baseline Emissions from Enteric Fermentation: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
India	265	274	283	293	301	0.7%
Brazil	225	236	237	236	234	0.2%
China	162	172	179	186	191	0.8%
United States	132	136	138	141	143	0.4%
Pakistan	73	81	90	100	111	2.1%

(continued)

Table 3-2: Projected Baseline Emissions from Enteric Fermentation: 2010–2030 ($MtCO_2e$) (continued)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Rest of Regions						
Asia	211	231	251	275	303	1.8%
Africa	277	302	325	349	374	1.5%
Europe	195	196	197	198	198	0.1%
Middle East	26	28	30	33	36	1.6%
Central & South America	218	235	248	261	272	1.1%
Eurasia	97	99	101	103	105	0.4%
North America	64	68	71	73	76	0.8%
World Totals	**1,945**	**2,059**	**2,150**	**2,246**	**2,345**	**0.9%**

Similarly, worldwide emissions from manure management are projected to increase at an average annual rate of 0.6% between 2010 and 2030, but that world average combines slower growth in the top-emitting countries with faster growth in the rest of regions. In 2010, the top five countries combine to account for 51% of global emissions from manure management. By 2030, these same five are projected to account for just under 50% of global emissions, equivalent to annual growth of 0.4%. In the rest of regions, global emissions grow at an average annual growth rate of 0.8%.

Table 3-3: Projected Baseline Emissions from Manure Management: 2010–2030 ($MtCO_2e$)

Country	2010	2015	2020	2025	2030	CAGR (2010–2030)
Top 5 Emitting Countries						
China	79	81	83	85	87	0.5%
United States	43	43	43	43	43	0.0%
India	35	37	39	40	42	0.9%
Brazil	10	10	11	11	12	0.8%
France	8	8	8	8	8	-0.4%
Rest of Regions						
Asia	56	60	65	70	76	1.5%
Africa	16	17	19	20	21	1.4%
Europe	53	53	52	52	52	-0.1%
Middle East	2	2	2	2	2	1.3%
Central & South America	9	10	10	11	11	1.2%
Eurasia	21	21	21	21	21	0.1%
North America	9	9	10	10	10	0.3%
World Totals	**341**	**352**	**362**	**373**	**384**	**0.6%**

V.3.3 Abatement Measures and Engineering Cost Analysis

A significant number of livestock GHG mitigation measures can be identified in the literature (e.g., Hristov et al., 2013; Archibeque et al. 2012; UNFCCC 2008, Whittle et al, 2013). However, developing consistent and regional-specific cost estimates for emerging mitigation measures or options that are not widely adopted has proven a challenging task. The measure cost data are scarce and often reflect anecdotal experience reported in a specific country, region or livestock production system. Assumptions have to be made to extrapolate the estimates in other countries, regions and production systems. This review uncovered only a few studies where cost information was presented in addition to associated emission reductions for a number of mitigation measures. Moreover, for some mitigation measures, such as those that potentially reduce livestock enteric fermentation CH_4 emissions, the literature varies on the estimated magnitude of emissions reductions as well as the long-term mitigation effects and animal and human health impacts.

Based on the availability and quality of mitigation measure cost and emission reduction efficiency information, this analysis evaluates six mitigation options for enteric fermentation CH_4 emissions and ten options for manure management CH_4 emissions. Each technology is briefly characterized followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis.

V.3.3.1 Enteric Fermentation CH_4 Mitigation Technologies

This section characterizes the mitigation technologies that can be applied to reduce enteric CH_4 emissions. Many of the currently available enteric fermentation mitigation options, summarized in Table 3-4, work indirectly by increasing animal growth rates and reducing time-to-finish (or increasing milk production for dairy cows). The potential GHG mitigation estimated here depends on the assumption that total production of meat or milk remains the same as in the baseline. Simply put, these strategies work because increased productivity means fewer animals are required to produce the same amount of meat or milk, and fewer animals mean reduced GHGs.

Unfortunately, many of the productivity enhancing options in this group are not without controversy (Hristov et al., 2013; Grainger et al., 2010). Some, such as bST and antibiotics, have raised concerns outside than their potential role in reducing GHGs. Most have greater than usual uncertainty about costs and effectiveness, especially under long term use. For example, Whittier et al. (2013), in developing MAC curves for Australia, assume that feed supplements (analogous to Improved Feed Conversion here) and antimethanogen vaccines will become available by 2020 for some types of livestock operations. However, ICF international, writing in a report prepared for the USDA, provides only a qualitative description of enteric fermentation GHG mitigation options, excluding them from cost or break-even analysis because "more research is needed to evaluate the potential GHG impacts of changes in diets, use of feed additives, and breeding (ICF International, 2013, p 3.62)."

In what follows we present descriptions and economic information used to derive the MAC curves. We examine the sensitivity of these results to productivity assumptions in Section V.3.5 which replaces the assumption of constant production with an assumption of constant animal population and also examines a no antimethanogen case.

Table 3-4: Abatement Measures for Enteric Fermentation CH_4

Abatement Option	Total Installed Capital Cost (2010 USD)	Annual O&M Cost (2010 USD)	Capital Lifetime (Years)	Reduction Efficiency (change in emissions per head)	Benefits (Changes in Livestock or Energy Revenue)
Improved Feed Conversion	0	25–295 per head	NA	CH_4: –39.4% to +39.6%	0–79% increase in animal yield
Antibiotics	0	4–9 per head	NA	CH_4: –0.4% to –6%	5% increase in animal yield
bST	0	123–300 per head	NA	CH_4: –0.2% to +10.3%	12.5% increase in animal yield
Propionate Precursors	0	40–120 per head	NA	CH_4: –10% beef cattle and sheep; –25% dairy animals	5% increase in animal yield
Antimethanogen	0	9–33 per head	NA	CH_4: –10%	5% increase in animal yield
Intensive Grazing	0	–180 to +1 per head	NA	CH_4: –13.3% beef cattle; –15.5% dairy cattle	–11.2% reduction in dairy cattle yield

Improved Feed Conversion

This mitigation measure encompasses a number of management practices that would improve the proportion of feed energy converted to final products. The practices include increased amount of grain fed to livestock, and inclusion of dietary additives. This option is more effective in reducing emissions in regions where baseline feed is of relatively low quality.

- **Annual Cost:** Typical annual costs for improving feed are between $2 and $295 per head for beef and dairy cattle. No data were identified for other species. One of the primary costs for this option, as well as most of the others below, is for additional labor costs necessary for implementation. Differences in labor input share and labor costs per hour are also major reasons for the wide variation in costs between regions and livestock production systems.
- **Annual Benefits:** Ration improvements result in an increase in yield (kg of meat or milk per animal) between 0 and 79%. There is considerable variation in the productivity impacts, primarily related to differences in baseline feed quality and productivity. Livestock raised in countries with low quality feeds in the baseline tend to have much greater productivity benefits from improved feed conversion than those in developed countries where feed conversion is already highly efficient.
- **Applicability:** This option applies to beef and dairy cattle in areas where baseline livestock growth rates and milk production are low, primarily developing regions including Africa. This option is assumed to be available only for urban livestock production or intensively managed livestock production and only applied in regions where the yield gains associated with the option are greater than baseline yield increases (typically limited to regions that do not already feed mixed rations).

- **Technical Efficiency:** This analysis assumes a change in emissions per head between -39% and +40%. Cases with increased emissions are excluded from the MAC analysis.[6]

Antibiotics

Feed antibiotics (e.g., monensin) to promote increased weight gain and reduce feed intake per metric ton of meat produced.

- **Annual Cost:** Typical annual costs for providing antibiotics are between $4 and $9 per head for beef cattle including the costs of antibiotics and increased labor costs for implementation. No data exist for other species.
- **Annual Benefits:** Ration improvements result in an increase in yield of 5% kg/animal
- **Applicability:** This option applies to beef cattle in all regions, but is restricted to urban livestock production and intensively managed livestock production.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head between 0% and 6%.

Bovine Somatrotropin (bST)

This measure administers bST to dairy cattle to increase milk production. Because of opposition to the use of growth hormones like bST in many countries, this option was only applied in a subset of countries.

- **Annual Cost:** Typical annual costs for purchasing and administering bST were estimated to be between $123 and $300 per head for dairy cows. This cost is based on the cost of purchasing bST and the additional labor costs required for administering.
- **Annual Benefits:** Using bST results in an average annual increase in yield (kg milk per head) of 12.5%
- **Applicability:** This option applies to dairy cows in all countries that currently approve the use of bST or are likely to do so in the near future. This option is assumed to be available only for urban or intensively managed livestock production.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head between 0% and 6%.

Propionate Precursors

This option involves administering propionate precursors (malate, fumarate) to animals on a daily basis. Hydrogen produced in the rumen through fermentation can react to produce either CH_4 or propionate. By adding propionate precursors to animal feed, more hydrogen is used to produce propionate and less CH_4 is produced.

- **Annual Cost:** Typical annual costs for purchasing and administering propionate precursors are between $40 and $120 per head for beef cattle, sheep, and dairy animals.
- **Annual Benefits:** Administering propionate precursors results in an increase in yield (kg of meat or milk per animal) of 5%.

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[6] For the primary scenario where production is held constant, options that increase emissions per unit of output are excluded from the MAC calculations. Thus, mitigation options that increase emissions per head are still included in the MAC calculations if they increase productivity more than then they increase emissions, resulting in a reduction in emissions intensity per unit of output.

- **Applicability:** This option applies to beef cattle, sheep, and dairy animals in all regions. However, as with other options, it is only applied in urban and intensive livestock production systems.
- **Technical Efficiency:** This analysis assumes a reduction in CH_4 emissions per head of 10% for beef cattle and sheep and a reduction of 25% for dairy animals.

Antimethanogen

Antimethanogen is a vaccine that can be administered to animals to suppress CH_4 production in the rumen. The vaccine is currently in infancy of development with limited information on emission reduction efficiency and long-term mitigation effects and animal health impacts.

- **Annual Cost:** Typical annual costs for providing antimethanogens are between $9 and $33 per head for purchasing and administering antimethanogens.
- **Annual Benefits:** Increases yields by 5% as more of the energy contained is feed is used by the animals to produce for meat or milk rather than producing methane
- **Applicability:** This option applies to all ruminants in all regions, though again it is assumed that only urban and intensively managed systems can adopt this option.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of 10%.

Intensive Grazing

Improving nutrition through more intensive pasture management and cattle rotations to allow for regrowth while decreasing reliance upon prepared rations.

- **Annual Cost:** Estimated reduction in yield of 11.2% for dairy cattle. Beef yields are assumed to remain unchanged under this option.
- **Annual Benefits:** Estimated annual cost savings of between $0 and $180 per head for reduced expenditures on feed.
- **Applicability:** This option applies only to beef and dairy cattle in developed regions and Latin America. It was assumed to be available only in intensively managed systems within livestock production system categories that receive relatively large amounts of annual rainfall such that intensive grazing is feasible.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 13-15%.

V.3.3.2 Manure Management CH_4 Mitigation Technologies

Mitigation options for reducing CH_4 from livestock manure focus on changes in manure management practices that capture the CH_4 to flare or use for energy production (see Table 3-5). There are fewer options for reducing N_2O emissions from manure because these emissions tend to result from decomposition under aerobic conditions, such as from pasture, range, and paddock where manure is much less concentrated and more difficult to manage.

This analysis includes both large capital-intensive digesters applied in developed regions and small-scale digesters for developing regions. Revenues are generated from the use of captured CH_4 for either heat or electricity on the farm; these revenues are scaled to other regions based on an electricity price index. Capital costs and O&M costs for digester systems are mainly based on the USEPA AgSTAR program data and experience in the U.S. and the developing countries (USEPA, 2010; Roos, personal communication 2012; Costa, personal communication 2012), supplemented by information from USDA (2007, 2011). For the EU, technology cost and performance parameters are based on Bates et al. (2009). For developing countries, the U.S. technology cost data are assumed for large digester systems with adjustments made to represent O&M costs in the developing countries. Capital costs for small-scale systems are based on USEPA (2006), which estimates the capital cost per 1,000 pounds liveweight. Because liveweight tends to be much smaller in developing countries, the capital cost per animal generally ends up being lower than in developed regions.

Table 3-5: Abatement Measures for Manure Management

Abatement Option	Total Installed Capital Cost (2010 USD)	Annual O&M Cost (2010 USD)	Capital Lifetime (Years)	Reduction Efficiency (change in emissions per head)	Benefits (Changes in Livestock or Energy Revenue)	Technical Applicability	Adjustments Across Regions
Complete-mix Digester, Hogs							
With Engine	100 per head (US)	0.11 per head (US)	20	CH_4: -85%	$8 energy revenue/ savings per head (US)	Hogs in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	61 per head (US)	0.07 per head (US)	20	CH_4: -85%	none	Hogs in selected LPS and management intensities	Labor costs, labor share
Complete-mix Digester, Dairy Cattle							
With Engine	958 per head (US)	3.35 per head (US)	20	CH_4: -85%	$65 energy revenue/ savings per head (US)	Dairy cattle in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	588 per head (US)	2.06 per head (US)	20	CH_4: -85%	none	Dairy cattle in selected LPS and management intensities	Labor costs, labor share
Plug-flow Digester, Dairy Cattle							
With Engine	1288 per head (US)	2.3	20	CH4: -85%	$65 energy revenue/ savings per head (US)	Dairy cattle in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	790 per head (US)	8.9	20	CH4: -85%	none	Dairy cattle in selected LPS and management intensities	Labor costs, labor share

(continued)

Table 3-5: Abatement Measures for Manure Management (continued)

Abatement Option	Total Installed Capital Cost (2010 USD)	Annual O&M Cost (2010 USD)	Capital Lifetime (Years)	Reduction Efficiency (change in emissions per head)	Benefits (Changes in Livestock or Energy Revenue)	Technical Applicability	Adjustments Across Regions
Fixed-film Digester, Hogs							
With Engine	128 per head (US)	0.15 per head (US)	20	CH_4: -85%	$8 energy revenue/ savings per head (US)	Hogs in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	102 per head (US)	0.12 per head (US)	20	CH_4: -85%	none	Hogs in selected LPS and management intensities	Labor costs, labor share
Covered Lagoon, Large-Scale, Hogs							
With Engine	43 per head (US)	0.13 per head (US)	20	CH_4: -85%	$8 energy revenue/ savings per head (US)	Hogs in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	25 per head (US)	0.06 per head (US)	20	CH_4: -85%	none	Hogs in selected LPS and management intensities	Labor costs, labor share
Covered Lagoon, Large-Scale, Dairy Cattle							
With Engine	1182 per head (US)	3.43 per head (US)	20	CH_4: -85%	$65 energy revenue/ savings per head (US)	Dairy cattle in selected LPS and management intensities	Labor costs, labor share, energy prices
Without Engine	773 per head (US)	2.01 per head (US)	20	CH_4: -85%	none	Dairy cattle in selected LPS and management intensities	Labor costs, labor share
Dome Digester, Cooking Fuel and Light	50 per 1000 lbs liveweight	1.25 per 1000 lbs liveweight	10	CH_4: -50%	$7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle	Hogs and dairy cattle in selected LPS and management intensities in developing countries	Labor costs, labor share, energy prices

(continued)

Table 3-5: Abatement Measures for Manure Management (continued)

Abatement Option	Total Installed Capital Cost (2010 USD)	Annual O&M Cost (2010 USD)	Capital Lifetime (Years)	Reduction Efficiency (change in emissions per head)	Benefits (Changes in Livestock or Energy Revenue)	Technical Applicability	Adjustments Across Regions
Polyethylene Bag Digester, Cooking Fuel and Light	20 per 1000 lbs liveweight	0.5 per 1000 lbs liveweight	10	CH_4: -50%	$7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle	Hogs and dairy cattle in selected LPS and management intensities in developing countries	Labor costs, labor share, energy prices
Centralized Digester	163 per head average for hogs across the EU, 1007 per head average for dairy cattle across the EU	0.07 per head for hogs, 2.06 dairy cattle	20	CH_4: -85%	$7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle	Hogs and dairy cattle in selected LPS and management intensities in the EU-27 region	Labor costs, labor share, energy prices

Complete-mix Digester

These digesters are more common in warmer climates, where manure is flushed out of barns or pens with water, lowering the solids' concentration to a level generally between 3 and 10%. Often there is a mixing tank where the manure accumulates before entering the digester. These digesters make use of gravity and pumps to move the manure through the system. They are often in the shape of a vertical cylinder and made of steel or concrete with a gas-tight cover. These digesters are typically heated to maintain a constant temperature and gas flow.

- **Capital Cost: $61/$100 per head (swine), $588/$958 per head (cattle) depending on optional engine**
- **Annual O&M Cost:** Estimated $0.07--$0.11 per head (swine), $2.06/3.35 (cattle)
- **Annual Benefits:** $8 per head (swine), $65 per head (cattle) if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine and cattle managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

Plug-flow Digester

These digesters consist of long and relatively narrow heated tanks, often built below ground level, with gas-tight covers. Plug-flow digesters are only used for dairy manure because they require higher manure solids' content, around 11 to 13%. As with complete-mix digesters, they are maintained at constant temperatures throughout the year to maintain constant gas production.

- **Capital Cost: $790/$1288 per head**
- **Annual O&M Cost:** Estimated $2.30 -- $8.90 per head
- **Annual Benefits:** $65 per head if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to dairy cattle in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

Fixed-film Digester

This digester option may be appropriate where concentrations of solids are very low, such as in swine manure management situations where manure is very diluted with water. Fixed-film digesters consist of a tank packed with inert media on which bacteria grow as a biofilm.

- **Capital Cost: $102/$128 per head**
- **Annual O&M Cost:** Estimated $0.06 -- $0.13 per head
- **Annual Benefits:** $8 per head if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

Large-scale Covered Lagoon

Covered earthen lagoons are the simplest of the systems used in developed countries and generally the least expensive, though there is quite a bit of variation in the systems that have been built. This system is used with low manure solids' concentration (less than 3%) and can be used for swine or dairy cattle. CH_4 is captured by covering the lagoon where manure is stored with a floating cover and piping the gas out to a flare or used on-farm. Because these digesters are not generally heated, the available gas flow varies significantly over the course of the year.

- **Capital Cost**: $25/$43 per head (swine), $773/$1,182 (cattle)
- **Annual O&M Cost:** Estimated $0.06/$0.13 per head (swine), $2.01/$3.43 (cattle)
- **Annual Benefits:** $8 per head (swine), $65 per head (cattle) if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine and dairy cattle managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

Small-scale Dome Digester

These are small, unheated digesters used in some developing countries, including China and India. A typical dome digester is a brick-lined cylinder sunk in the ground with a wall dividing the cylinder in two with inlet and outlet ports connected to the bottom of the tank. Biogas generated is typically used by the household for cooking and other household energy needs.

- **Capital Cost:** $50 per 1,000 lbs liveweight
- **Annual O&M Cost:** Estimated $1.25 per 1,000 lbs liveweight

- **Annual Benefits:** $7 per head (swine), $48 per head (cattle)
- **Applicability:** This option applies to swine and dairy cattle in developing regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 50%.
- **Capital Lifetime:** 10 years

Centralized Digester

Large centralized digesters where individual farmers transport their waste to in order for large scale digestion and dispersion of capital costs.

- **Capital Cost:** $163 per head (swine) , $1,007 per head (cattle)
- **Annual O&M Cost:** Estimated $0.07 per head (swine), $2.06 per head (cattle)
- **Annual Benefits:** Assumed to provide the same annual benefits per head of livestock as the large individual systems described above.
- **Applicability:** This option applies only to swine and dairy cattle in intensively managed production systems in EU-27 regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

V.3.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-CO_2 sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

This section describes the general modeling approach applied in this sector, which serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

V.3.4.1 Development of Disaggregated Baseline Livestock Populations

Livestock population projections at a disaggregated level are a key component of estimating potential emissions reductions from livestock production. Tables 3-6 and 3-7 present baseline projected livestock populations by species at the global and regional levels, respectively. As noted earlier in this chapter, these projections are based on country-level livestock population data from USEPA (2012), adjusted using livestock production and market price projections from Nelson et al. (2010) to derive projected livestock populations.

Table 3-6: Projected Global Livestock Populations by Species

Species	2010	2015	2020	2025	2030
Asses	43,694,545	44,710,040	46,511,983	49,232,861	53,072,574
Mules	10,687,809	9,719,699	9,087,894	8,688,065	8,454,990
Buffalo	181,068,216	190,207,386	200,872,941	213,277,930	227,690,865
Camels	25,230,544	27,116,465	29,660,950	33,095,191	37,758,103
Cattle	1,141,799,067	1,233,755,944	1,293,778,238	1,348,359,726	1,392,273,902

(continued)

Table 3-6: Projected Global Livestock Populations by Species (continued)

Species	2010	2015	2020	2025	2030
Dairy cattle	247,195,753	248,770,901	250,894,992	253,588,443	256,874,692
Goats	882,119,170	947,475,133	1,035,241,803	1,151,801,402	1,306,127,535
Horses	58,864,443	59,669,740	61,198,242	63,481,024	66,580,631
Other camelids	6,926,082	7,090,544	7,260,388	7,435,790	7,616,931
Pigs	947,222,554	963,684,813	981,443,858	1,000,597,025	1,021,251,228
Sheep	1,126,923,912	1,264,771,843	1,421,729,708	1,600,736,874	1,805,223,246
Turkeys	488,712,578	506,073,755	524,421,101	543,822,679	564,352,297
Chickens	18,934,787,428	20,500,590,776	22,251,209,335	24,210,358,750	26,405,046,832
Ducks	1,156,375,916	1,288,661,778	1,437,928,802	1,606,439,449	1,796,773,159
Geese	365,742,348	404,547,438	447,801,893	496,016,058	549,759,182

The livestock populations were disaggregated into 14 categories of livestock production systems (LPSs) based on the Gridded Livestock of the World (Robinson et al., 2011), along with an "UNKNOWN" category that was added to account for cases where there were no data available to assign a livestock species to an LPS:

- LGA – livestock only grassland arid and semiarid
- LGH – livestock only grassland humid and subhumid
- LGT – livestock only grassland highland temperate
- LGY – livestock only grassland hyper arid
- MIA – irrigated mixed crop-livestock systems arid and semiarid
- MIH – irrigated mixed crop-livestock systems humid and subhumid
- MIT – irrigated mixed crop-livestock systems highland temperate
- MIY – irrigated mixed crop-livestock systems hyper arid
- MRA – rainfed mixed crop-livestock systems arid and semiarid
- MRH – rainfed mixed crop-livestock systems humid and subhumid
- MRT – rainfed mixed crop-livestock systems highland temperate
- MRY – rainfed mixed crop-livestock systems hyper arid
- URBAN – built-up areas
- OTHER – other systems
- UNKNOWN – no data available to assign to LPS

Table 3-7: Regional Livestock Populations by Species, 2010 and 2030

	Asses	Mules	Buffalo	Camels	Cattle	Dairy Cattle	Goats	Horses	Pigs	Sheep	Turkeys	Chickens	Ducks	Geese
2010														
AFRC	19,060,943	1,077,045	5,339,864	21,477,486	220,327,356	58,488,802	299,505,213	4,709,306	27,178,558	304,049,685	17,230,236	1,452,628,008	16,880,560	12,657,925
MIEA	2,749,155	198,708	753,069	1,247,756	8,021,314	5,567,448	45,065,821	225,902	214,307	109,243,396	6,102,128	845,345,519	1,886,081	2,092,632
CSAM	3,798,475	2,955,700	1,111,814	309,916,289	37,138,939	25,161,984	17,250,838	6,926,082	69,414,647	79,203,085	57,089,883	2,434,716,295	8,424,513	425,747
EURO	846,866	281,198	425,943	1,208	76,446,634	30,849,246	20,260,700	4,593,009	163,465,255	141,794,134	101,594,263	1,660,083,208	44,889,390	14,050,300
EURA	677,880	1,068	343,107	221,501	29,855,690	23,418,817	12,030,080	4,071,274	28,727,659	78,557,745	18,007,749	664,246,895	11,508,213	8,305,203
ASIA	13,249,225	2,862,090	173,094,419	2,282,593	362,788,699	79,456,157	468,038,089	11,512,981	563,373,447	398,701,823	2,955,455	9,099,019,576	1,056,093,702	327,903,127
NAAM	3,312,000	3,312,000	—	—	134,443,085	12,276,345	12,057,283	16,501,133	94,848,681	15,374,043	285,732,864	2,778,747,928	16,693,456	307,414
2030														
AFRC	28,605,408	1,410,927	9,840,993	33,269,240	266,035,319	73,540,139	432,866,460	7,753,070	37,167,402	537,137,245	19,285,366	1,916,766,477	21,622,904	15,777,661
MIEA	2,742,926	197,774	1,165,203	1,503,917	10,420,595	6,127,068	53,996,856	238,226	212,496	181,275,748	7,462,777	993,216,019	2,251,984	2,547,450
CSAM	3,525,580	2,565,528	876,235	363,165,169	34,416,861	24,447,270	17,058,230	7,616,931	87,526,659	123,946,758	79,940,136	3,293,431,862	11,572,205	620,925
EURO	609,117	234,846	1,008,184	4,597	78,327,604	27,596,465	20,202,782	5,548,271	153,126,179	192,995,324	102,791,593	1,706,164,516	44,614,600	13,888,742
EURA	849,921	844	282,435	442,251	33,053,022	21,338,795	24,550,502	5,634,282	27,922,758	130,930,762	18,608,201	700,410,055	12,039,543	8,669,961
ASIA	13,427,623	733,070	214,517,815	2,538,098	487,150,416	82,381,796	735,097,827	10,892,381	624,250,619	614,909,005	3,991,403	14,449,006,323	1,683,405,389	507,862,027
NAAM	3,312,000	3,312,000	—	—	154,121,776	11,473,568	14,965,839	19,456,171	91,045,115	24,028,403	332,272,820	3,346,051,579	21,266,535	392,416

Note: AFRC = Africa; MIEA = Middle East; CSAM = Central and South America; EURO = Europe; EURA = Eurasia; ASIA = Asia; NAAM = North America

The LPSs capture major combinations of livestock production systems of the world with respect to land use type and climate. Livestock populations across livestock production systems were assigned for pigs, goats, sheep, dairy cattle, and beef cattle based on the country-level data from Robinson et al. (2011). Approximation was made for the distribution of selected species where LPS data were not available.

In addition to disaggregation by LPS, certain livestock species were further disaggregated into production intensity categories. For pigs, data were provided by the Food and Agriculture Organization (FAO) that separated country-level pig populations into three intensity categories for each LPS: intensive, semi-intensive, and extensive. Those data were used to assign intensity levels to pig populations and this distribution was used as a proxy for poultry production intensity in countries with both pig and poultry production. For beef and dairy cattle, regional allocation of cattle across intensity categories in Robinson et al. (2011) was used to assign intensity levels to each country located within that region. For other species, all intensity levels were defined as unknown. As an example, Table 3-8 presents the assumed distribution of livestock across livestock production systems and intensity classifications for India, the largest emitter for the livestock production sector.

The detailed disaggregation of baseline populations allows for better definition of the technical applicability of mitigation options. For instance, this study only applies large-scale digesters to intensive dairy and hog production systems in each country. Intensive grazing is assumed to be applicable only to relatively high productivity mixed crop-livestock systems that rely on irrigation or are in humid and subhumid or temperate highland LPS designations. The use of a highly disaggregated baseline in this study serves to define the share of emissions where mitigation options can potentially be applied.

Enteric fermentation and manure management emissions for each subset of livestock populations were calculated using the IPCC default values consistent with those used in USEPA (2012). The one exception is for enteric fermentation emissions in Africa, where relative emissions reported in Robinson et al. (2011) were used to scale default IPCC emissions per head for different LPS categories.

Table 3-8: Livestock Distribution by Intensity and Livestock Production System for India, 2010 (% of animals by species)

Species	Intensity	LGA	LGH	LGT	LGY	MIA	MIH	MIT	MIY	MRA	MRH	MRT	MRY	URBAN	Other
Asses	unknown	0.5%	0.1%	0.0%	0.0%	31.7%	6.6%	0.0%	0.0%	40.2%	11.0%	1.3%	0.0%	7.3%	1.2%
Mules	unknown	0.5%	0.1%	0.0%	0.0%	31.7%	6.6%	0.0%	0.0%	40.2%	11.0%	1.3%	0.0%	7.3%	1.2%
Buffalo	unknown	0.5%	0.1%	0.0%	0.0%	31.7%	6.6%	0.0%	0.0%	40.2%	11.0%	1.3%	0.0%	7.3%	1.2%
Camels	unknown	0.5%	0.1%	0.0%	0.0%	31.7%	6.6%	0.0%	0.0%	40.2%	11.0%	1.3%	0.0%	7.3%	1.2%
Cattle	intensive	0.3%	0.1%	0.0%	0.0%	17.7%	3.7%	0.0%	0.0%	22.4%	6.2%	0.7%	0.0%	4.1%	0.7%
Cattle	extensive	0.2%	0.0%	0.0%	0.0%	12.6%	2.6%	0.0%	0.0%	16.0%	4.4%	0.5%	0.0%	2.9%	0.5%
Cattle	unknown	0.0%	0.0%	0.0%	0.0%	1.4%	0.3%	0.0%	0.0%	1.8%	0.5%	0.1%	0.0%	0.3%	0.1%
Dairy Cattle	intensive	0.2%	0.1%	0.0%	0.0%	18.6%	3.9%	0.0%	0.0%	21.0%	6.5%	0.8%	0.0%	4.1%	0.7%
Dairy Cattle	extensive	0.2%	0.0%	0.0%	0.0%	13.3%	2.8%	0.0%	0.0%	15.0%	4.6%	0.5%	0.0%	3.0%	0.5%
Dairy Cattle	unknown	0.0%	0.0%	0.0%	0.0%	1.5%	0.3%	0.0%	0.0%	1.7%	0.5%	0.1%	0.0%	0.3%	0.1%
Goats	unknown	1.8%	0.0%	0.0%	0.0%	34.6%	7.0%	0.0%	0.0%	39.0%	7.9%	1.3%	0.0%	7.2%	1.3%
Horses	unknown	0.5%	0.1%	0.0%	0.0%	31.7%	6.6%	0.0%	0.0%	40.2%	11.0%	1.3%	0.0%	7.3%	1.2%
Pigs	intensive	0.0%	0.5%	0.1%	0.0%	13.8%	3.0%	0.3%	0.0%	7.1%	16.9%	5.2%	0.0%	2.6%	0.5%
Pigs	extensive	0.0%	0.0%	0.0%	0.0%	14.6%	2.0%	0.0%	0.0%	12.0%	4.3%	0.5%	0.0%	4.1%	0.5%
Pigs	semi-intensive	0.0%	0.1%	0.0%	0.0%	3.3%	0.7%	0.1%	0.0%	1.7%	4.0%	1.2%	0.0%	0.6%	0.1%
Sheep	unknown	3.4%	0.0%	0.0%	0.0%	30.8%	5.0%	0.1%	0.0%	45.5%	5.1%	2.6%	0.0%	6.8%	0.7%
Chickens	intensive	0.0%	0.5%	0.1%	0.0%	13.8%	3.0%	0.3%	0.0%	7.1%	16.9%	5.2%	0.0%	2.6%	0.5%
Chickens	extensive	0.0%	0.0%	0.0%	0.0%	14.6%	2.0%	0.0%	0.0%	12.0%	4.3%	0.5%	0.0%	4.1%	0.5%
Chickens	semi-intensive	0.0%	0.1%	0.0%	0.0%	3.3%	0.7%	0.1%	0.0%	1.7%	4.0%	1.2%	0.0%	0.6%	0.1%
Ducks	intensive	0.0%	0.5%	0.1%	0.0%	13.8%	3.0%	0.3%	0.0%	7.1%	16.9%	5.2%	0.0%	2.6%	0.5%
Ducks	extensive	0.0%	0.0%	0.0%	0.0%	14.6%	2.0%	0.0%	0.0%	12.0%	4.3%	0.5%	0.0%	4.1%	0.5%
Ducks	semi-intensive	0.0%	0.1%	0.0%	0.0%	3.3%	0.7%	0.1%	0.0%	1.7%	4.0%	1.2%	0.0%	0.6%	0.1%

V.3.4.4 MAC Analysis Results

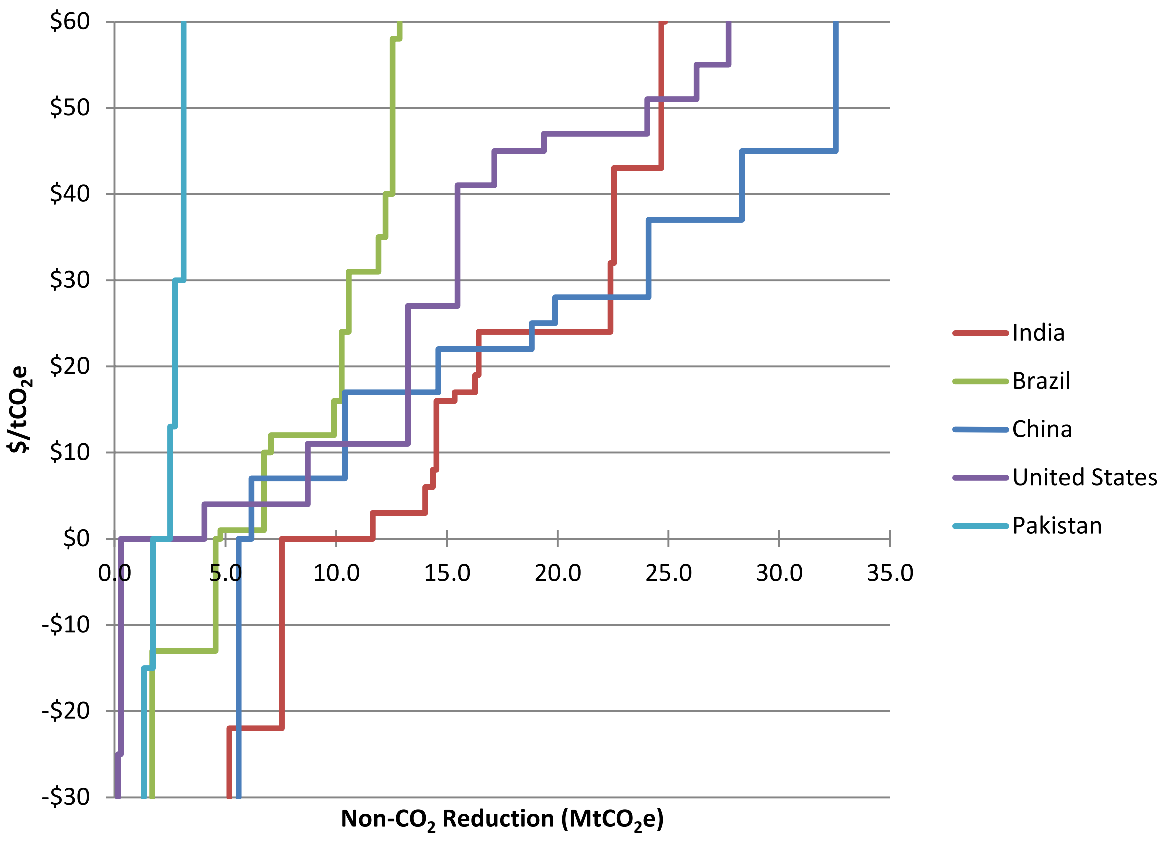
As highlighted at the beginning of this chapter, global abatement potential in the livestock sector equates to approximately 3% of its total annual emissions between 2010 and 2030 at no or a relatively low carbon price of $5 per ton of CO_2 equivalent ($/t$CO_2$e). In 2030, total abatement potential in the livestock sector is 70 MtCO_2e at no carbon price, 86 MtCO_2e at a carbon price of $5/t$CO_2$e, and 128 Mt$CO_2$e at a carbon price of $20/t$CO_2$e, representing 2.6%, 3.2% and 4.7% of the total sector emissions, respectively. Table 3-9 presents the estimated mitigation potential at various break-even prices for the top-five emitting countries and rest of regional groups in 2030 under an assumption that livestock populations adjust to maintain production at baseline levels when mitigation options result in changing productivity.

Table 3-9: Abatement Potential by Region at Selected Break-Even Prices in 2030 (MtCO_2e), Baseline Production Case

	Break-Even Price ($/t$CO_2$e)										
Country/Region	**–10**	**–5**	**0**	**5**	**10**	**15**	**20**	**30**	**50**	**100**	**100+**
Top 5 Emitting Countries											
India	7.6	7.6	11.7	14.0	14.5	14.5	16.4	22.4	24.7	25.0	27.4
China	5.6	5.6	6.2	6.2	10.4	10.4	14.6	24.1	32.6	35.5	38.3
Brazil	4.6	4.6	4.8	6.7	7.1	9.9	10.2	10.6	12.5	13.2	13.6
United States	0.3	0.3	4.1	8.7	8.7	13.2	13.2	15.5	24.0	37.5	43.2
Pakistan	0.7	1.7	2.5	2.5	2.5	2.7	2.7	3.1	3.1	4.4	5.6
Rest of Region											
Africa	8.7	9.3	11.8	12.3	12.6	12.9	13.1	13.3	13.6	14.0	14.6
Asia	12.3	13.6	18.1	21.2	24.8	26.3	30.2	35.0	38.1	40.4	45.5
Central & South America	5.8	6.4	7.8	8.9	10.4	11.1	12.6	13.1	14.2	14.8	15.2
Eurasia	1.2	1.3	1.4	1.5	1.6	1.6	1.6	1.6	1.8	2.0	2.7
Europe	6.2	6.4	10.7	11.0	11.3	12.4	15.5	16.4	20.9	29.7	50.6
Middle East	1.5	1.5	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.9
North America	1.3	1.7	2.5	2.5	2.6	3.8	4.4	5.0	6.2	9.2	10.0
World Total	**55.7**	**60.0**	**83.3**	**97.2**	**108.1**	**120.5**	**136.3**	**161.6**	**193.3**	**227.5**	**268.6**

Mitigation potential and its cost-effectiveness vary significantly by country or region. At the regional level, Asia (in particular South and Southeast Asia), Africa, Central and South America and the European Union show the most significant potential for reducing GHG emissions from livestock operations. For instance, in 2030 mitigation potential in Asia is estimated to be 27 MtCO_2e with no carbon price and 34 MtCO_2e at a carbon price of $20/t$CO_2$e. Central and South America can achieve mitigation potential of 12 MtCO_2e in 2030 at no carbon price, and mitigation potential can increase to 22 MtCO_2e at a carbon price of $20/t$CO_2$e. Figure 3-5 shows the MAC curves for the top-five emitting countries in 2030.

Figure 3-5: Marginal Abatement Cost Curve for Top 5 Emitters in 2030 (Baseline Production Case)

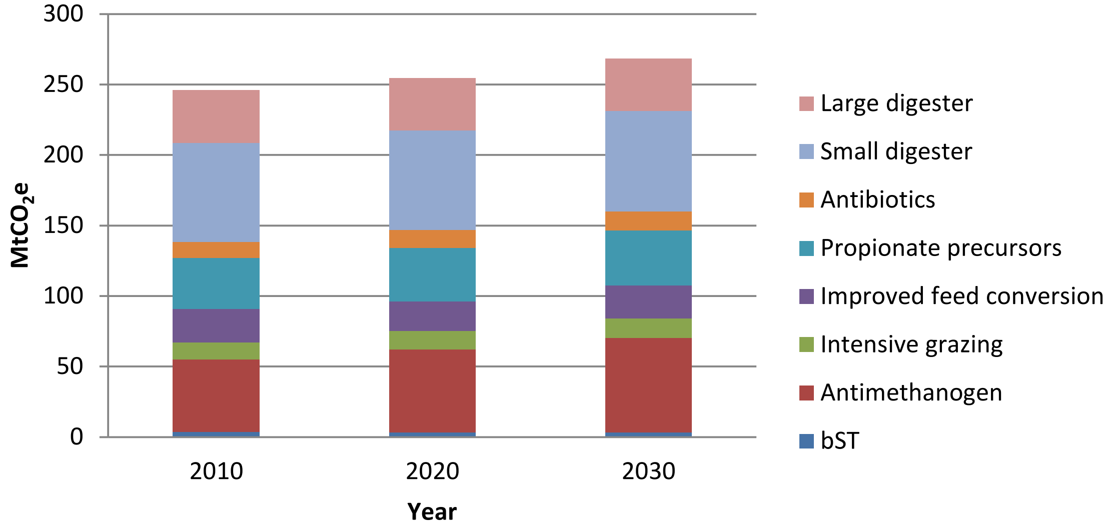


The MAC analysis also suggests that mitigation of enteric fermentation methane emissions presents the most cost-effective mitigation opportunity for options evaluated in this report. Manure management mitigation measures mostly require additional investments or financial incentives to achieve emissions reductions. The most cost-effective mitigation options for the livestock sector (i.e., measures that dominate the MAC curves at break-even carbon prices at or below \$0/MtCO2e) include:

- intensive grazing in East Asia (e.g., Japan, Korea and China) and Central and South America;
- BST administered to dairy cattle in developing regions;
- antimethanogens administered to sheep and goats as well as beef and dairy cattle;
- improved feed conversion efficiency of the cattle populations; and
- propionate precursors administered to beef and dairy cattle in developing regions

Figure 3-6 shows the distribution of mitigation potential across individual types of options at a global scale based on total technical potential (regardless of price) calculated in the MAC analysis.

Figure 3-6. Global Net GHG Livestock Emissions Reduction Potential by Mitigation Option (Baseline Production Case)



V.3.5 Sensitivity Analyses

In this section, we explore sensitivity analyses to examine the potential effects on estimated mitigation potential. Although many of the mitigation options examined are expected to increase productivity and would therefore require fewer animals to produce the same amount of output, livestock populations may not decrease accordingly. Due to increasing demand for livestock products and potential reductions in the price of these products with higher productivity, the quantity of livestock products demanded may increase. Thus, we examine an alternative scenario that holds the number of livestock constant at the projected baseline populations. To the extent that productivity is increased by adoption of the GHG mitigation options considered, this scenario will result in higher global production. In addition, given mixed conclusions on the near-term prospects of antimethanogens, we also present mitigation estimates developed excluding antimethanogens as an option.

Baseline Number of Animals

As noted above, many of the mitigation options in the baseline production case reduce the emissions per unit of meat or milk but may increase the emissions per animal. This section explores this relationship further by presenting an alternative scenario built around a constraint on the number of animals, keeping the herd sizes the same as estimated in the baseline.

As before, the MAC model only includes options that result in lower emissions. But with the number of animals held constant, those mitigation strategies that increase emissions per animal in a given region are excluded in that region. The result is 15 to 39% lower mitigation potential as shown in Figure 3-7 and Table 3-10.

Figure 3-7: Global Abatement Potential in Livestock Management, Baseline Number of Animals : 2010, 2020, and 2030

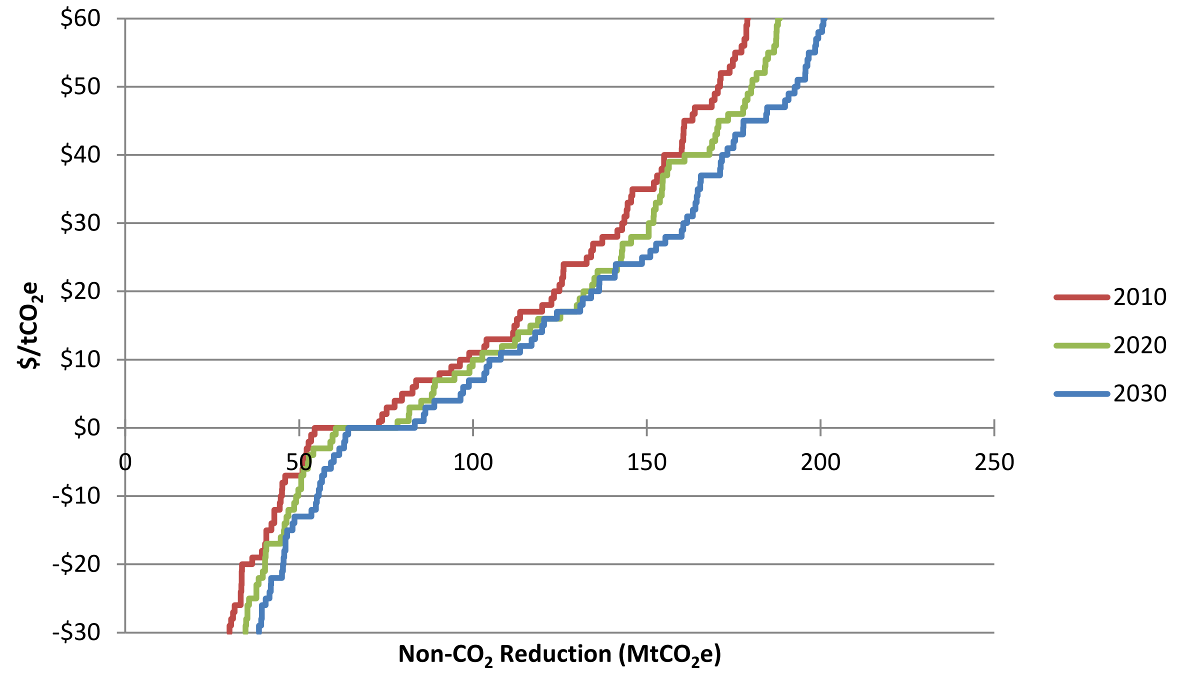


Table 3-10: MAC Results and Differences from Constant Production Case for Baseline Number of Animals Scenario

	2010		2020		2030	
$/tCO$_2$e	Total Reduction MTCO$_2$e	Difference from Constant Production (%)	Total Reduction MTCO$_2$e	Difference from Constant Production(%)	Total Reduction MTCO$_2$e	Difference from Constant Production (%)
0	49	-21%	54	-19%	60	-15%
5	58	-20%	61	-22%	65	-25%
10	65	-27%	68	-27%	73	-25%
15	79	-25%	78	-29%	81	-26%
20	84	-29%	88	-31%	87	-31%
25	86	-33%	91	-33%	97	-33%
30	90	-35%	97	-34%	101	-35%
35	93	-37%	98	-34%	106	-33%
40	96	-39%	101	-39%	109	-35%
45	98	-39%	103	-39%	113	-37%
50	102	-39%	108	-39%	118	-38%

No Antimethanogen

The science and policy literature varies in its treatment of antimethanogens. The Australian government included them in their recent study (Whittle et al., 2013). However ICF International, in a recent analysis for USDA, concludes that "more research is needed to evaluate the potential GHG impacts of changes in diets, use of feed additives, and breeding." (ICF International, 2013) For comparison purposes we estimated MAC curves as above except by assuming antimethanogens are unavailable in all regions and time periods. Results are shown in Figure 3-8 and Table 3-11. Globally, the mitigation potential in the livestock sector is reduced 16 to 31% in the scenario with no antimethanogens and baseline production.

Figure 3-8: Global Abatement Potential in Livestock Management, Baseline Production with No Antimethanogen: 2010, 2020, and 2030

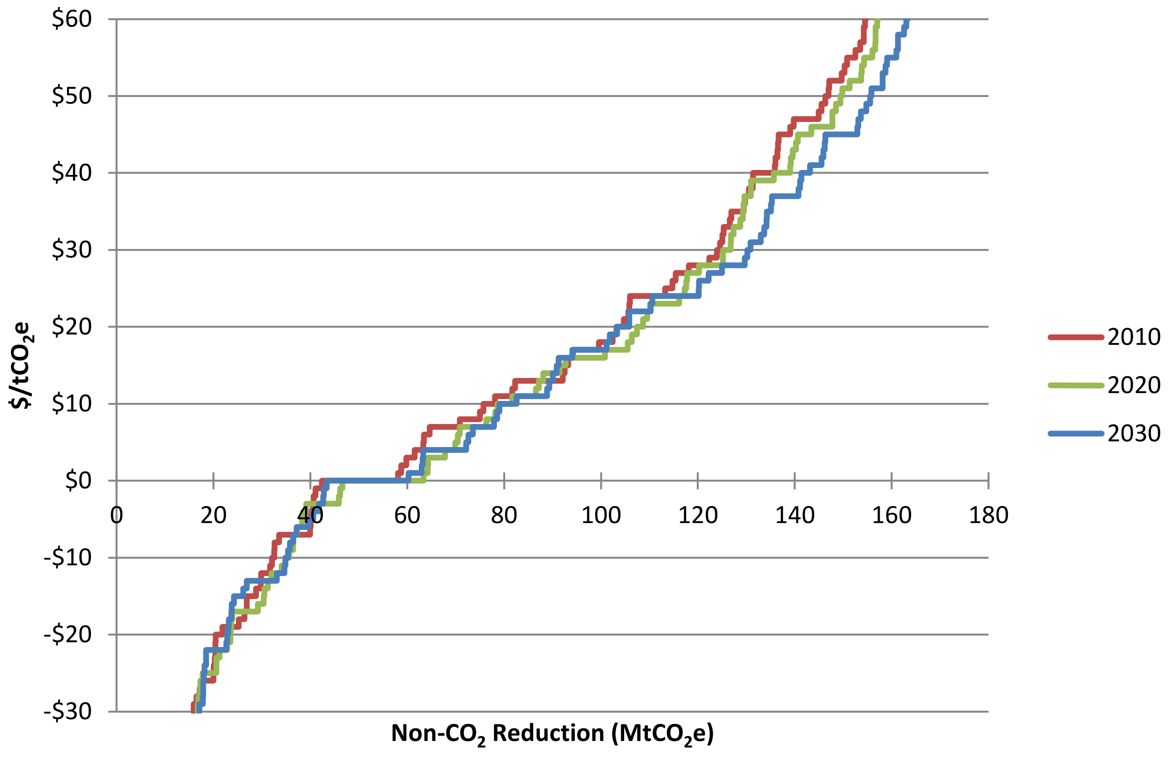


Table 3-11: MAC Results and Differences from Constant Production Case for No Antimethanogen Scenario

$/tCO₂e	2010 Total Reduction MTCO₂e	2010 Difference from Constant Production (%)	2020 Total Reduction MTCO₂e	2020 Difference from Constant Production(%)	2030 Total Reduction MTCO₂e	2030 Difference from Constant Production (%)
0	48	-28%	53	-20%	49	-31%
5	54	-31%	61	-22%	62	-28%
10	70	-25%	73	-21%	73	-25%
15	87	-21%	85	-23%	82	-26%
20	99	-22%	103	-19%	98	-23%
25	110	-19%	113	-18%	115	-20%
30	120	-18%	122	-16%	126	-19%
35	126	-15%	125	-16%	130	-18%
40	133	-19%	136	-17%	139	-17%
45	136	-20%	140	-17%	149	-17%
50	145	-18%	147	-17%	152	-20%

Combined Baseline Number of Animals and No Antimethanogen

Results for a combined scenario including both an assumption that the number of livestock under the mitigation scenario remains equal to the baseline and no applicability of antimethanogens are presented in Figure 3-9 and Table 3-12. Under this scenario, there is a reduction in mitigation potential of between 16 and 43% relative to the primary case where production of livestock products is assumed to remain equal to baseline levels.

Figure 3-9: Global Abatement Potential in Livestock Management, Baseline Number of Animals with No Antimethanogen: 2010, 2020, and 2030

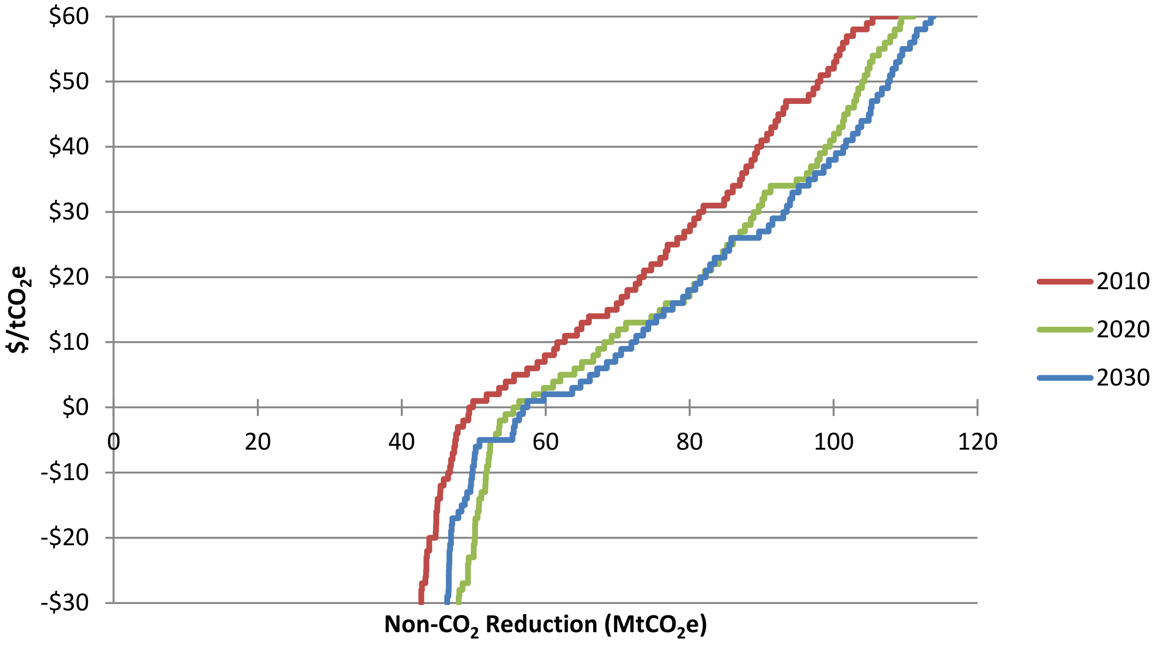


Table 3-12: MAC Results and Differences from Constant Production Case for Combined Baseline Number of Animals and No Antimethanogen Case

	2010		2020		2030	
$/tCO₂e	Total Reduction MTCO₂e	Difference from Constant Production (%)	Total Reduction MTCO₂e	Difference from Constant Production (%)	Total Reduction MTCO₂e	Difference from Constant Production (%)
0	50	-20%	56	-16%	57	-18%
5	57	-21%	64	-18%	67	-22%
10	63	-30%	69	-26%	73	-26%
15	70	-34%	77	-31%	78	-30%
20	74	-38%	82	-36%	82	-35%
25	78	-39%	86	-37%	86	-41%
30	82	-41%	90	-39%	94	-40%
35	87	-41%	96	-35%	97	-39%
40	90	-42%	100	-39%	102	-39%
45	93	-42%	102	-40%	105	-41%
50	98	-42%	104	-41%	108	-43%

Change in Production of Livestock Products with Number of Animals Held at Baseline Levels

For the scenario where livestock populations are kept at projected baseline levels, there will be changes in production of livestock products due to changes in output per head for many options. Figures 3-10 and 3-11 show the change in global beef production and global milk production from dairy cattle estimated if all production were to switch from baseline management into that option.

Figure 3-10: Global Beef Production under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant

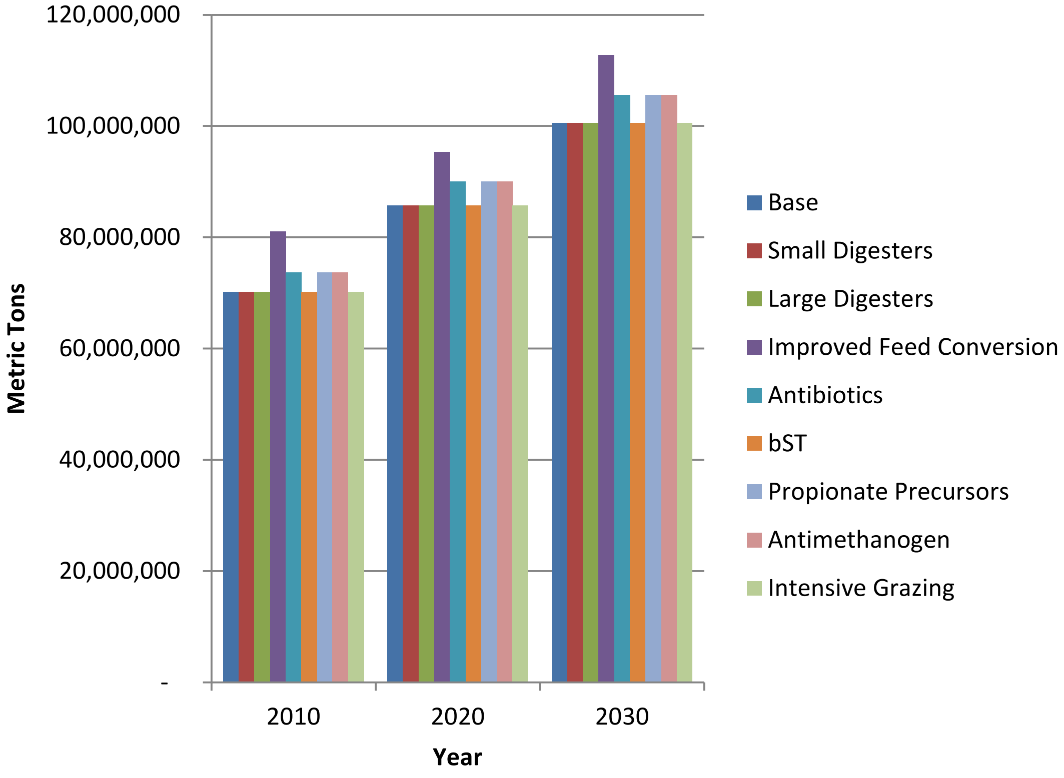
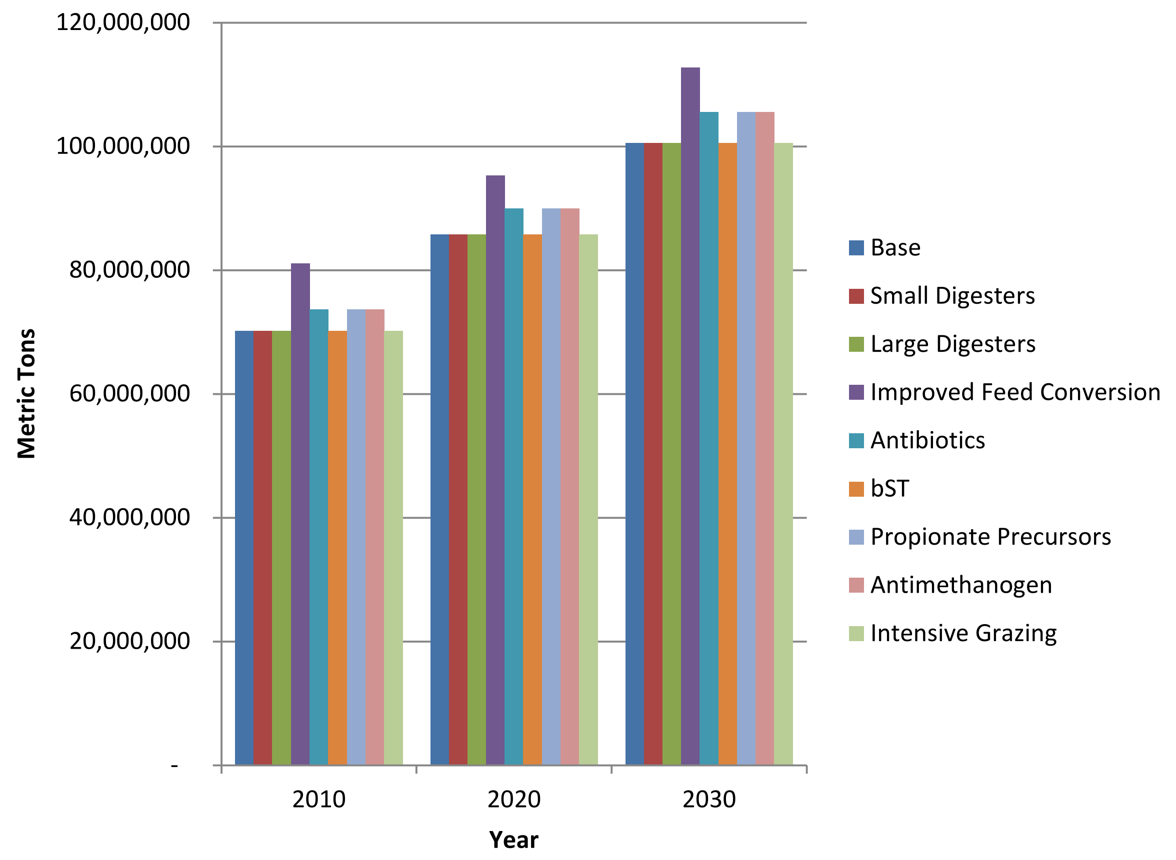


Figure 3-11: Global Production of Milk from Dairy Cattle Under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant



V.3.4.5. Uncertainties and Limitations

Given the complexities of the global livestock sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Availability and quality of data to represent the highly complex and heterogeneous livestock production systems of the world.*** Although there are major improvements in the characterization of the business-as-usual baseline conditions since the previous EPA report (USEPA, 2006), data in some areas, such as management practices, are not always available for all countries or regions and approximations must be made based on limited literature or expert judgment.
- ***Availability of mitigation measure cost data and in some cases scientific understanding of mitigation impacts.*** Collecting and developing consistent cost estimates of emerging mitigation measures or options that are not widely adopted has proven to be challenging. Moreover, scientific understanding of the mitigation effects and animal and human health impacts of some mitigation measures is still limited. In addition, some mitigation measures, such as pasture management options that lead to reductions in enteric CH_4 emissions and enhancement in soil carbon storage, would require a different analytical framework that is beyond the scope of this study.

- ***Optimistic assumptions on technology adoption.*** The analysis assumes that if mitigation technology is considered feasible in a country or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially inhibit the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). Adoption of the various technologies and management practices (such as supplementation) faces even greater challenges. The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.
- ***Potential market feedback from livestock productivity improvement.*** The analysis assumes constant production level when evaluating mitigation potential of abatement measures. This analysis does not, however, address the possibility of an emissions increase as a result of lower costs per unit through such efficiency gains, which could in turn increase the quantity demanded.
- ***Potential interactions of multiple mitigation measure.*** In this analysis, mitigation options are applied to independent segments of the livestock populations to avoid double counting. In reality, multiple mitigation options can be applied and their potential interactions may affect the aggregate GHG mitigation. For example, various measures can improve feed conversion efficiency (e.g., concentrate inclusion, dietary additives such as oils) and their effectiveness would depend on the other measures implemented; measures that reduce CH_4 emissions from manure management (e.g., aeration) would likely increase N_2O emissions; measures that improve feed conversion efficiency would likely change N_2O emissions in livestock manure; measures that improve diet quality for grazing livestock would likely change GHG emissions from agricultural soils. The interactive effects are not fully addressed in this analysis.

References

Archibeque, S., Haugen-Kozyra, K., Johnson, K., Kebreab, E., & Powers-Schilling, W. (2012). Near-Term Options for Reducing Greenhouse Gas Emissions from Livestock Systems in the United States: Beef, Dairy, and Swine Production Systems. Nicholas Institute for Environmental Policy Solutions Report NI R12-04, July 2012.

Bates, J., N. Brophy, M. Harfoot and J. Webb. (2009). Agriculture: methane and nitrous oxide. Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC). pp. 62.

Costa, A. (2012). Personal communication.

Grainger, C., R. Williams, R. J. Eckard, and M. C. Hannah. 2010. A high dose of monensin does not reduce methane emissions of dairy cows offered pasture supplemented with grain. J. Dairy Sci. 93:5300-5308.

Hristov, A.N., J. Oh, C. Lee, R. Meinen, F. Montes, T. Ott, J. Firkins, A. Rotz, C. Dell, A. Adesogan, W. Yang, J. Tricarico, E. Kebreab, G. Waghorn, J. Dijksta, and S. Oosting. 2013. *Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO2 emissions.* Edited by Pierre J. Gerber, Benjamin Henderson and Harinder P.S. Makkar. FAO Animal Production and Health Paper No. 177. FAO: Rome, Italy.

ICF International, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production in the United States. February 2013.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T.B. Sulser, C. Ringler, S. Msangi, and L. You. (2010). Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. International Food Policy Research Institute: Washington, DC.

Robinson, T.P., Thornton P.K., Franceschini, G., Kruska, R.L., Chiozza, F., Notenbaert, A., Cecchi, G., Herrero, M., Epprecht, M., Fritz, S., You, L., Conchedda, G. & See, L. (2011). Global livestock production systems. Rome, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI), 152 pp.

Roos, K. (2012). Personal communication.

U.S. Department of Agriculture, Economic Research Service (USDA, ERS). February 2011. *Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations.* ERR-111. U.S. Department of Agriculture, Economic Research Service.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). October 2007. *Analysis of Energy Production Costs of Anaerobic Digestion Systems of U.S. Livestock Production Facilities.* Available at: http://www.agmrc.org/media/cms/manuredigesters_FC5C31F0F7B78.pdf.

U.S. Environmental Protection Agency (USEPA) (2006). Global Mitigation of Non-CO2 Greenhouse Gases. EPA 430-R-06-005. Washington DC.

USEPA (2010). *Anaerobic Digestion Capital Costs for Dairy Farms*. Washington, DC: U.S. Environmental Protection Agency. Available at: http://www.epa.gov/AgSTAR/pdf/digester_cost_fs.pdf.

USEPA. (2012). *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2030*. EPA 430-R-12-006. Washington, DC: USEPA.

Whittle, L., Hug, B., White, S., Heyhoe, E., Harle, K., Mamun, E., & Ahammad, H. (2013). Costs and Potential of Agricultural Emissions Abatement in Australia. Australian Bureau of Agricultural and Resource Economics and Sciences. Technical Report 13.2, March 2013.

Williams, Y. J., S. Popovski, S. M. Rea, L. C. Skillman, A. F. Toovey, K. S. Northwood, and A. D. G. Wright. 2009. A vaccine against rumen methanogens can alter the composition of archaeal populations. Appl. Environ. Microbiol. 75:1860–1866.

World Resources Institute (WRI). (2012). Climate Analysis Indicators Tool (CAIT) database. Available at http://www.wri.org/project/cait/.

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