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Global Non-CO₂ Greenhouse Gas Emission Projections & Marginal Abatement Cost Analysis: Methodology Documentation

Report

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U.S. Environmental Protection Agency
Office of Atmospheric Programs,
Climate Change Division
Washington, DC

Prepared by

RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

Abt Associates, Inc.
10 Fawcett Street
Cambridge, MA 02138

ICF
9300 Lee Highway
Fairfax, VA 22031



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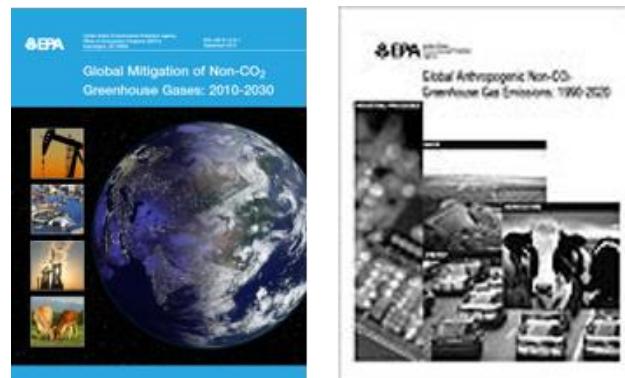
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1 Background and Introduction

This peer-reviewed document outlines methodologies developed and used by the U.S. Environmental Protection Agency (EPA) to calculate global non-carbon dioxide (non-CO₂) greenhouse gas (GHG) projections and mitigation potential. The methodological approach for emission projections was used to estimate historical non-CO₂ GHG emission estimates for individual countries and sectors from 1990 to 2015, and emission projections from 2020 through 2050, at 5-year intervals. The methodological approach for calculating non-CO₂ GHG mitigation potential builds off the emission projections and was used to generate marginal abatement cost (MAC) curves, where each point on the cost curve reflects the average price and reduction potential for mitigation technologies. This document updates and combines two prior report series, *Non-CO₂ Greenhouse Gases: International Emissions and Projections* [EPA, 2006, 2012] and *Global Mitigation of Non-CO₂ Greenhouse Gases* (EPA, 2005, 2013).

Combining the “Projections” and “Mitigation” reports provides an opportunity to better align these two documents and their respective uses. The period of analysis has been extended from 2030 through 2050. The EPA also intends to make the combined results available electronically to decrease the time required between updates and to facilitate use of the latest estimates.



The “Projections” report included historical data; the latest country-reported emission estimates; and a methodology for estimating non-CO₂ emission projections using a combination of country-reported data and calculations based on the Intergovernmental Panel on Climate Change (IPCC) inventory. The projections methodology appears in Section 3. This methodology update introduces greater disaggregation of major sources, based on magnitude or trends in emissions, providing higher resolution on subsource contributions to total emissions. The emission projections are a composite of country-reported historical emission estimates and trends based on projected activity data. The results are a “business-as-usual” (BAU) scenario with fixed emission factors and reflect the impact of GHG emission reduction policies and measures to the extent those are reflected in country-reported historical emissions. The projections include the impact of existing GHG reduction policies to the extent they are reflected in historical data but exclude additional GHG reductions because of current and additional planned activities and economy-wide programs that would reduce emission rates from historical levels.

The “Mitigation” report estimated technical and economic potential mitigation of non-CO₂ GHG emissions for 20 sectors and 195 countries. The mitigation methodology is presented in Section 4. The mitigation methodology includes several new developments, including incorporating the impact of technology change on abatement costs and emission reductions globally and developing a regionalized set of MAC curves that provide increased heterogeneity in abatement costs and emission reductions for the United States by state. Additionally, this methodology incorporates new data on mitigation technologies, costs, and country-reported emission baselines.

Finally, a major focus of mitigation methodology development has been greater harmonization with the projections; specifically, we attempted to use the projections as the “baseline” values to which mitigation technical and economic potentials are compared when possible and investigate ways in which the estimates may be made more compatible.

The results of the analysis will be presented in a forthcoming accompanying report as emission projections and MAC curves for 195 individual countries as well as overall trends by region, gas, and source category for the

years 2020 through 2050. Emission abatement will be shown in both absolute and percentage reductions from the baseline.

The remainder of this methodology document provides additional detail on the projections and MAC modeling approaches. Section 2 provides a brief overview of the non-CO₂ GHGs and their global warming potentials (GWPs). Section 3 provides a detailed description of the methodology used to prepare emission trajectories by source for 1990 through 2050, including a discussion of the sources of uncertainties associated with developing these emission estimates. Section 4 describes the general methodology for the MAC analysis. Sections 4.1 describes the anatomy of the MAC curve and the limitations and uncertainties associated with the MAC calculations. Section 4.2 provides a more detailed description of the major methodological enhancements, accounting for technical change and developing a more regionalized U.S. MACs. Section 5 includes additional methodological detail for the 27 individual non-CO₂ emitting sources analyzed within the energy, industrial, agricultural, and waste sectors. The technical and economic characteristics of each mitigation option, specific modeling considerations, and projected baseline emissions are also described by sector and region.

2 Non-CO₂ GHGs

The gases included in this report are the direct non-CO₂ GHGs covered by the United Nations Framework Convention on Climate Change (UNFCCC): methane (CH₄), nitrous oxide (N₂O), and fluorinated greenhouse gases (F-GHGs) that include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), and nitrogen trifluoride (NF₃). These non-CO₂ GHGs are more potent than CO₂ (per unit weight) at trapping heat within the atmosphere. Additionally, some non-CO₂ GHGs can remain in the atmosphere for longer periods of time than CO₂. This report does not include compounds covered by the Montreal Protocol. Table 2-1 lists the source categories for the non-CO₂ GHGs considered for this analysis.

Table 2-1: Sources Included in This Report

Sector/Source	Gas
Energy	
Natural Gas and Oil Systems	CH ₄
Coal Mining Activities	CH ₄
Stationary and Mobile Combustion	CH ₄ , N ₂ O
Biomass Combustion	CH ₄ , N ₂ O
Other Energy	CH ₄ , N ₂ O
Industrial Processes	
Adipic Acid and Nitric Acid Production	N ₂ O
Use of Substitutes for Ozone-Depleting Substances ^a	HFCs
HCFC-22 Production	HFCs
Electric Power Systems	SF ₆
Primary Aluminum Production	PFCs
Magnesium Manufacturing	SF ₆
Electronics Manufacturing ^b	HFCs, PFCs, SF ₆ , NF ₃
Other Industrial Processes	CH ₄ , N ₂ O
Agriculture	
Agricultural Soils	N ₂ O
Enteric Fermentation	CH ₄
Rice Cultivation	CH ₄
Manure Management	CH ₄ , N ₂ O
Other Agriculture	CH ₄ , N ₂ O
Waste	
Landfilling of Solid Waste	CH ₄
Wastewater	CH ₄ , N ₂ O
Other Waste	CH ₄ , N ₂ O

^aSubstitutes for ODSs include uses in refrigeration and air conditioning (AC), solvents, foams, aerosols, and fire extinguishers.

^bElectronics manufacturing includes semiconductors, photovoltaic, and flat panel displays.

2.1 GWPs Assigned to Non-CO₂ GHGs

The GWP compares the relative ability of each GHG to trap heat in the atmosphere during a certain time frame. Per IPCC (2007) guidelines, CO₂ is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH₄ is 25 and the GWP of N₂O is 298. Table 2-2 lists all GWPs used in this report to convert the non-CO₂ emissions into CO₂-equivalent units. This report uses GWPs from the 2007 IPCC Fourth Assessment Report.

2.2 Methane (CH₄)

CH₄ is approximately 25 times more powerful at warming the atmosphere than CO₂ over a 100-year period. Additionally, the chemical lifetime for CH₄ in the atmosphere is approximately 12 years, compared with approximately 100 years for CO₂. These two factors make CH₄ 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 CH₄ could respond to mitigation actions.

Man-made sources of CH₄ include coal mining natural gas and oil systems, stationary and mobile combustion, certain industrial processes, agricultural activities, landfills, and wastewater treatment. CH₄ is also a primary component of natural gas and an important energy source. As such, both the prevention and capture of CH₄ emissions can provide significant energy, economic, and environmental benefits.

2.3 Nitrous Oxide (N₂O)

A clear, colorless gas with a slightly sweet odor, N₂O is an important GHG because of its long atmospheric lifetime (approximately 114 years) and heat-trapping effects that are about 298 times more powerful than CO₂.

N₂O comes from natural and man-made sources and is removed from the atmosphere mainly by photolysis (i.e., breakdown by sunlight) in the stratosphere. In the United States, the main man-made sources of N₂O are agricultural soil management, livestock waste management, mobile and stationary fossil fuel combustion, adipic acid production, and nitric acid production. N₂O is also produced naturally from a variety of biological sources in soil and water, although this report covers anthropogenic sources only.

Table 2-2: GWPs from the IPCC Fourth Assessment Report

Greenhouse Gas	GWP ^a
CO ₂	1
CH ₄	25
N ₂ O	298
HFC-23	14,800
HFC-32	675
HFC-125	3,500
HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-4310mee	1,640
NF ₃	17,200
CF ₄	7,390
C ₂ F ₆	12,200
C ₄ F ₁₀	8,860
C ₆ F ₁₄	9,300
SF ₆	22,800

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. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.) Cambridge, United Kingdom: Cambridge University Press.

^a100-year time horizon.

2.4 Fluorinated Gases (F-GHGs)

There are three major categories or types of F-GHGs: HFCs, PFCs, SF₆ and NF₃. These compounds are the most potent GHGs because of their large heat-trapping capacity and, in the cases of the PFCs and SF₆, 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-GHGs are emitted from a broad range of industrial sources; most of these gases have few (if any) natural sources.

2.4.1 Hydrofluorocarbons (HFCs)

HFCs are man-made 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 124 (HFC-152a) to 14,800 (HFC-23). The atmospheric lifetime for HFCs varies from just over a year (HFC-152a) to 270 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).

2.4.2 Perfluorocarbons (PFCs)

Primary aluminum production, semiconductor manufacturing and flat panel display manufacturing are the largest known man-made sources of the PFCs tetrafluoromethane (CF₄) and hexafluoroethane (C₂F₆). PFCs are also relatively minor substitutes for ODSs. Over a 100-year period, CF₄ and C₂F₆ are, respectively, 7,400 and 12,200 times more effective than CO₂ at trapping heat in the atmosphere.

2.4.3 Sulphur Hexafluoride (SF₆)

The GWP of SF₆ is 22,800, making it the most potent GHG evaluated by IPCC. SF₆ 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, SF₆ is very long-lived, so all man-made sources contribute directly to its accumulation in the atmosphere.

2.4.4 Nitrogen Trifluoride (NF₃)

NF₃ is used in the manufacturing of semiconductors, photovoltaic cells, and flat panel displays. Over a 100-year period, NF₃ is 17,200 times more effective than CO₂ at trapping heat in the atmosphere. NF₃ was added as a GHG under the Kyoto Protocol for its second commitment period.

2.5 References

Intergovernmental Panel on Climate Change. 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. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.) Cambridge, UK: Cambridge University Press.

3 Baseline Emissions Calculation—General Methodology

The general approach for developing the estimates of historical and projected emissions used a combination of publicly available emission estimates from nationally prepared GHG reports with the EPA-estimated emissions consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (1996 IPCC Guidelines) (IPCC, 1997), the

IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC Good Practice Guidance) (IPCC, 2000), and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (2006 IPCC Guidelines) (IPCC, 2006). To project

emissions, the EPA used drivers based on globally available growth

rates or activity data specific to each source. The EPA's calculated emission estimates were prepared in a consistent manner across all countries using IPCC default methodologies, international statistics for activity data, and the IPCC Tier 1 default emission factors.¹ Higher IPCC tiers (i.e., Tier 2 and Tier 3) would be more accurate but require more specific data requirements, so data limitations prohibited EPA from using higher tier calculations across all countries, sectors, and subsources. Mitigation options represented in the MAC curves reduce emissions from the baseline projections described in this section.

Baseline Projections

In this report, the terms “business as usual,” “BAU,” and “baseline” all refer to the non-CO₂ emission projection results and are used interchangeably.

The EPA prepared a complete set of non-CO₂ GHG emission estimates, regardless of available country-reported estimates, to produce a complete global inventory. Depending on available information, the projected emission estimates for each country and source are either (1) a composite of historical country-reported emissions and calculated estimates or (2) calculated estimates based on IPCC default emission factors and globally available activity data. In most cases, some country-reported data are available, so the composite approach was used. The second approach was only used where no country-reported data are available for a source category. For estimates based on the composite approach, the Tier 1-calculated emission estimates were used to determine trends through the time series, but the emission factors (i.e., emissions per unit of activity data) derive primarily from country-reported information.

The projections estimates used both Excel workbooks and R programs. Source-specific calculations, based on a Tier 1 calculation methodology,² were performed in individual analysis workbooks. These source-specific analyses were subsequently inputted into a program using R programming language to develop a composite of emissions for the time series of 1990 through 2050.³ The EPA used the R programming language to streamline the projections updating process, as well as to centralize the calculations necessary to combine Tier 1 estimates from the individual analysis workbooks with country-reported estimates.

The remainder of this section is organized as follows:

- Section 3.1 presents an overview of the main data sources for reported emission estimates and calculations
- Section 3.2 presents the general methodology for calculating emission estimates from activity data and emission factors using methods based on Tier 1 methodologies from IPCC inventory guidelines.

¹ IPCC inventory guidelines generally include up to three different “tier” emissions methodologies that provide different levels of complexity and require different data or country-specific information. Tier 1 is the simplest of the three and often involves default emissions factors that can be used where country-specific emissions factors are not available.

² In cases where a Tier 1 methodology was not feasible, estimates were based on another established methodology consistent across all countries using IPCC default methodologies. However, for the purposes of this report, estimates calculated by the EPA are referred to as “Tier 1” emissions calculations.

³ R is an open-source programming language and software environment.

- Section 3.3 discusses the steps taken to develop the final composite emission estimates from the combination of country-reported and calculated estimates.

3.1 Data Sources

For Annex 1 (A1) countries, the primary source of data for historical emission estimates was data from National Inventories Common Reporting Format (CRF) files reported to the UNFCCC (UNFCCC, 2018a). The CRF data contain reported national inventory data from 1990 through 2016. For Non-Annex 1 (Non-A1) countries, the primary source of data for historical emission estimates was data from the UNFCCC flexible query system (UNFCCC, 2016).⁴ The UNFCCC flexible query system contains historical CH₄, N₂O, and F-GHG emission estimates reported to the UNFCCC. Data for Non-A1 countries obtained through the UNFCCC flexible query system contained data reported through country national communication and biennial update reports. In some cases, more recent data reported through country national communication and biennial update reports were not available through the UNFCCC flexible query system and were obtained directly from the reports (UNFCCC, 2018b) or from the UNFCCC Greenhouse Gas Data Interface (UNFCCC, 2018c).

Activity data were obtained from publicly available sources with global activity data, such as the U.S. Energy Information Administration (EIA) and the U.N. Food and Agriculture Organization (FAO). Emission factors were obtained from the 2006 IPCC Guidelines (IPCC, 2006).

Country-reported emission projections are also available from the UNFCCC from Biennial Reports. However, these projections are only available aggregated at either the gas group or sector level for the years 2020 and 2030, for A1 countries. For this reason, country-reported projections could not be used for source- and gas-specific projections.

Additional data to inform emission reduction activities, activity data, and emission factor calculations were obtained from a literature review of academic papers and other databases, which are cited in the source-specific methodology discussions.

3.1.1 Comparative Analysis

The EPA also obtained data from the European Commission’s Emissions Database for Global Atmospheric Research (EDGAR) (EC-JRC, 2016), and the International Institute for Applied Systems Analysis- Greenhouse Gas–Air Pollution Interactions and Synergies (IIASA-GAINS) database (IIASA, 2016) to perform a series of comparative analyses. The EPA used IIASA-GAINS and EDGAR data to compare to the projections generated to observe and analyze similarities and differences in the projections.

Additionally, a comparative analysis was performed between the composite results and the previous EPA published report (EPA, 2012) on the source category- and sector-levels in order to assess the consistency of results with previous projections. Composite results were also compared to other data sources, such as EDGAR and IIASA, to confirm any observed trends and examine sector-level results.

3.2 Calculating Historical and Projected Non-CO₂ Emissions

EPA first calculated Tier 1 emission estimates using IPCC Tier 1 methodology, IPCC Tier 1 emission factors, and projected activity data through 2050 for all sources and countries. All sources have calculated emissions that rely

⁴ As identified by the UNFCCC, A1 countries include all Organisation for Economic Co-operation and Development (OECD) countries in 1992, plus countries with economies in transition and several Central and Eastern European States. Non-A1 countries include the rest of the world, consisting of developing countries in South America, Africa, and Asia. For more information on the distinction between A1 and Non-A1 countries, see:

http://unfccc.int/parties_and_observers/items/2704.php.

on emission factors that are fixed throughout the time series. Key parameters and assumptions for the independent set of calculated estimates include:

- For the purposes of calculating projections, the base year for this analysis is the last historical year of emissions reported by a country. For details on the last historical year of reported estimates by country, please see Appendix B.
- If a country reported no emissions in a given source in the base year all future emissions were assumed to be zero.
- GWPs from the IPCC’s Fourth Assessment Report (IPCC, 2007) were used to convert non-CO₂ emissions to CO₂-equivalent emissions (CO₂e).⁵
- The country list included in the analysis is the same as that of the last publication, using the State Department as a reference, except for two new countries: Kosovo and South Sudan.
- A subset of source categories was considered priority because of their magnitude or projected trend over the time series: natural gas and oil systems, coal mining activities, adipic acid and nitric acid production, landfilling of solid waste, substitutes for ODSs, and wastewater.
- Projection results were disaggregated for the following source categories using Tier 1 estimate proportions:
 - Nitric and adipic acid production were disaggregated into nitric acid and adipic acid production.
 - Wastewater was disaggregated into urban and rural sources.
 - Coal mining activities were disaggregated into above- and under-ground estimates.
 - Natural gas and oil systems were disaggregated into gas production; gas transmission, storage, and distribution; oil production; and oil refining.
 - Substitutes for ODSs were disaggregated into refrigeration/air-conditioning, foams, solvents, aerosols, and fire extinguishers.
 - Biomass combustion was disaggregated into biofuels and wood fuel/charcoal.

Section 3.3 provides a detailed description of the methodology used to prepare emission trajectories that combine the calculations described in this section with country-reported emission estimates by source, including a discussion on the sources of uncertainties associated with developing these emission estimates.

3.3 Generating the Composite Historical and Projected Non-CO₂ Emissions

To use information from both country-reported and Tier 1-calculated emission estimates, the EPA used a composite emission methodology, identical to that used in the previous report (EPA, 2012), to combine these two datasets in a consistent manner. This methodology, described in detail below, creates a complete time series that is consistent with country-reported data, when available, and fills in gaps using Tier 1-calculated emission estimates.

⁵ The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to a reference gas, CO₂. The IPCC updated GWPs in the IPCC Fourth Assessment Report (AR4) (IPCC 2007) which resulted in significantly different values for some of the gases compared to previously used values in the IPCC Second Assessment Report (SAR) (IPCC, 1996). For example, the GWP of methane (CH₄) has increased from 21 in the SAR to 25 in the AR4, whereas the GWP of N₂O has decreased from 310 in the SAR to 298 in the AR4. As such, some of the historical CO₂e values in this report may look significantly different than the values in previous versions of the report due to the changes in GWPs of individual gasses. For a complete list of GWP values see the IPCC Fourth Assessment Report (AR4) (IPCC, 2007). AR4 GWP values were chosen to remain consistent with the GWP-weighted country reported emissions used to develop projections.

After completing the individual dataset of Tier 1 IPCC-calculated estimates, as described in Section 3.2, EPA then reviewed for and pulled in any country-reported historical estimates.

- A1 Countries: A full time series of data, disaggregated at the source category and subsource category levels, was available and used as the estimates for A1 countries from CRF files from 1990 through 2016.
- Non-A1 Countries: Historical emission data from Non-A1 countries were available in the UNFCCC flexible query system, UNFCCC detailed data by party system, country national communication reports, and country biennial reports, but generally these reported data did not constitute a full time series and are sometimes available at the source, rather than subsource, level (e.g., A1 countries report emissions from nitric and adipic acid production separately, while Non-A1 countries report aggregated emissions). To calculate emission estimates for 1990, 1995, 2000, 2005, 2010, and 2015, gaps in the reported estimates were filled by linear interpolation (when missing data occurred between 2 years with reported data) or backcasting/projecting (by applying growth rates from each source category's activity data, when missing data occur outside of years with reported data).

UNFCCC country-reported data were mapped to corresponding Tier 1 calculations using UNFCCC source and gas combinations. Because the UNFCCC estimates were available at different levels of disaggregation for A1 and Non-A1 countries, these data were mapped to the corresponding Tier 1 calculations at the source level (see Table 3-1).

Table 3-1: UNFCCC Source Category Mappings to the EPA Source Categories (Example)

UNFCCC Source Category	EPA's Source Category
1.A Fuel Combustion	Stationary and Mobile Combustion
1.B.2 Oil and Natural Gas	Oil and Natural Gas Systems

Upon completion of the mapping of the reported dataset to the calculation dataset for a given source, a set of operations was performed in the R code to (1) linearly interpolate any data gaps for intermediate years; (2) back cast years in which reporting began after 1990, using the growth rates of the Tier 1 calculations to estimate for missing historical years; and (3) project emissions beyond the years reported using the growth rates of the Tier 1 calculations.

Countries without historical reported emissions were pulled in “as is” from the individual analysis files. This prioritization process is summarized in the following steps:

1. If country-reported historical data exist, they were used to populate the historical years, 1990 through 2016, which is the latest possible year of available country-reported estimates at the time of the analysis.

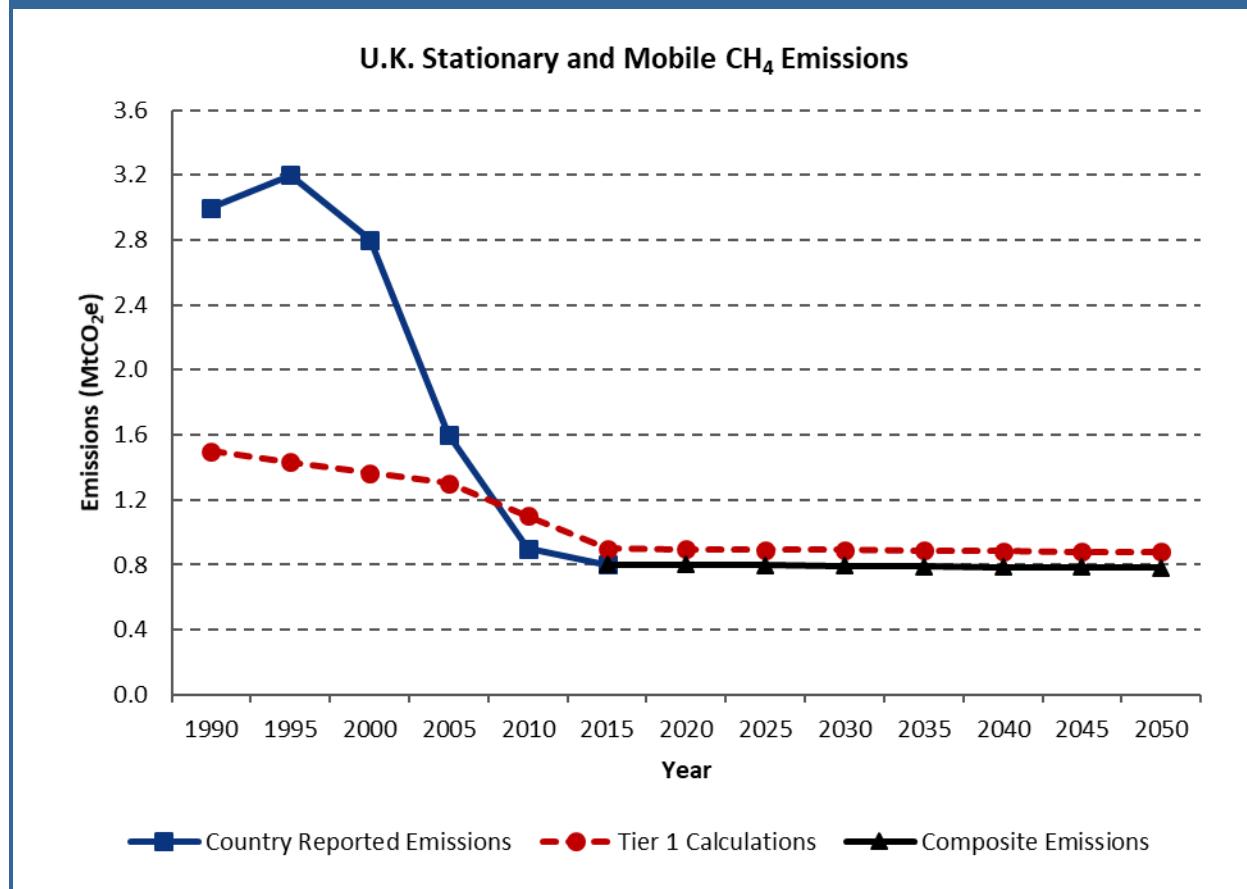
Composite Approach Key Drivers

- **Projected Trends.** The composite approach relies on EPA Tier 1-calculated estimates to determine increases and/or decreases to emissions through the time series. This is because country-reported emission projections are not generally available disaggregated by gas and source; additionally, activity data projections are limited in that emission source categories often combine multiple activities with different characteristics.
- **Emission Factors.** The composite approach does not have a specific set of emission factors that corresponds to any particular estimates. Because the starting point is country-reported data, emission factors associated with the composite projections derive primarily from the country-reported estimates. See Section 3.3.1 for additional discussion.

2. For those countries, the EPA projected emissions from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For example, if the Tier 1 calculations indicate a 2015 through 2020 growth rate of 5%, followed by a 2020 through 2050 growth rate of 10%, the composite calculation increases that country's reported 2015 emissions by 5% to the year 2020, and then by 10% through 2050.
3. For countries and sources that do not have country-reported historical data, the EPA used the emission estimates calculated by the Tier 1 methodology as the full time series from 1990 through 2050.

Figure 3-1 provides a visual example of how country-reported and Tier 1 calculations were combined.

Figure 3-1: Example of Combining Country-Reported and Tier 1 Calculations



This process was performed consistently for all countries, sources, and gases. For sources that included subsources, the composite results were disaggregated based on the proportion of Tier 1-calculated emissions from each subsource. The composite results for individual sources were extracted as outputs from the R code, indicating subsource when available.

The “Other” categories in each sector are included for completeness and solely comprise countries that report data to the UNFCCC database. The EPA did not perform Tier 1 calculations for “Other” source categories. The EPA obtained historical country-reported estimates for the “Other” categories for 1990 through 2012 and held 2015 through 2050 emission estimates constant at 2012 levels for each country.

3.3.1 Emission Factors in the Composite Projections

Because most of the emission projections are based on a combination of country-reported and calculated emission estimates, it is not straightforward to specify the emission factor that corresponds to any particular projection estimate. The starting point for these projections is country-reported data, so the emission factor, or emissions per unit of activity data differ between countries based on the differing calculations that countries have incorporated into their emission inventories. The Tier 1 source-specific calculations are based on a BAU scenario, which generally keep fixed emission factors over time. These calculations use IPCC default emission factors; however, these are not necessarily representative of the emission factors for the resulting composite projections. Additionally, in many cases, a source category aggregates emissions for several smaller subsources or categories. For example, enteric fermentation estimates are driven by estimates for a variety of different animals. For the composite projections, the IPCC default factors are more significant for disaggregation of subsources and as weighting factors between the relative trends of different categories within a source category.

3.3.2 Reductions in the Baseline Scenario

Although the baseline or BAU scenario generally does not explicitly model emission reduction policies undertaken by individual countries, and the default IPCC factors generally reflect uncontrolled emissions, the composite emission projections do include historical emission reductions. To the extent that emission reductions are reflected in country-reported base year data, those rates are used throughout the projection time series. Thus, the degree to which reductions are included in a particular estimate corresponds to the extent to which reductions are reflected in country-reported data.

3.3.3 Excluded Data

During the review of composite results, the EPA compared country-reported emission estimates to Tier 1-calculated estimates to identify cases where data in the country-reported datasets may have been misreported or transcribed incorrectly. As a result, a small number (<0.5%) of country-reported data points were excluded. Two main metrics were used to identify potential errors: the ratio and difference between country-reported and Tier 1-calculated emission estimations for the last year of reported data. The country-reported emission estimates that were reviewed by EPA included those that met any one of the following criteria:

- a difference greater than 500 Gg with Tier 1-calculated emission estimates,
- the highest 2% of differences,
- a ratio greater than 20 of country-reported emission estimates to Tier 1-calculated emission estimates, and
- the highest 2% of ratios.

The quantitative screening resulted in a list of several hundred data points that were reviewed by source experts. Based on the EPA's review of the country-reported emission estimates that met the above criteria, 16 country-reported estimates were excluded from the composite calculations. The EPA believes these discrepancies may have resulted from differences in units, calculations, or problems with data entry in the UNFCCC system and may not represent countries' current estimates of emissions. Incorporating these data discrepancies would have resulted in a significant change in projected emissions for some sources and countries in the composite results.

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4 MAC Analysis—General Methodology

The basic methodology is a bottom-up, engineering cost approach and is the same methodology used for the 2013 report (EPA, 2013a). MAC curves were constructed for each region and sector by estimating the carbon price at which the present-value benefits and costs for each mitigation option equilibrate. 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 (MtCO₂e).

The mitigation option analysis throughout this report was conducted using a common methodology and framework. This section outlines the basic methodology. The sector-specific sections describe the mitigation estimation methods in greater detail, including any necessary deviations from the basic methodology.

The MAC model continues to offer improvements made in the 2013 report, which included

- 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 adjustment factors used to construct country-specific abatement costs and benefits; and
- updating crop process model simulations of changes in crop yields and emissions associated with rice cultivation and cropland soil management.

4.1 Methodology Overview

The abatement analysis for all non-CO₂ emissions from sources in the agriculture, energy, waste, and industrial process sectors is based on EPA (2013a) and improves on Ragnauth et al. (2015), Gallaher et al. (2005), and Rose et al. (2013). These studies provided estimates of potential CH₄ and N₂O emission reductions from major emitting sectors and quantified costs and benefits of these reductions. Mitigation analysis accounts for country differences in industry structure and available infrastructure where data are available on a sector-by-sector basis. For example, the analysis of the natural gas and oil sector relied on country-specific activity data on production, processing/refining, and transportation infrastructure to distribute baseline emissions to specific subsectors. Additionally, we accounted for country/regional differences in price of mitigation through a series of international cost indices (labor, nonenergy materials, energy) to create a more heterogeneous representation of emissions and mitigation costs and benefits across countries. Thus, the EPA analysis provides significant detail at the sector and subsector levels and across countries.

Given the detailed data available for U.S. sectors, our analysis of the United States used representative facility estimates but then applied the estimates to a highly disaggregated and detailed set of emission sources for all the major sectors and subsectors. For example, the EPA analysis of the natural gas sector was based on more than 100 emission sources in that industry, including gas well equipment, pipeline compressors and equipment, and system upsets. Thus, the EPA analysis provides significant detail at the sector and subsector levels.

The analysis generally began 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 were based on detailed U.S. and European Union (EU) inventory estimates and were then extrapolated 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 was available and was incorporated into the model.

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

The agricultural sector's emission abatement analysis improves on analyses in previous studies supported by the EPA (2013a) that generated MAC curves by major world region for cropland N₂O CH₄ and soil carbon, livestock enteric CH₄, manure management N₂O and CH₄, and rice cultivation N₂O and CH₄. Updates in this report include the following:

- regionalized livestock estimates for the United States
- more explicit links to the baseline projection estimates

4.1.1 Technical Characteristics of Abatement Options

The non-CO₂ abatement options evaluated in this report were compiled from the studies mentioned above and from the sector-specific literature. For each region, either the entire set of sector-specific options or the subset of options determined to be applicable was applied. Options were 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. Furthermore, 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 4-1 summarizes how the potential emission reduction was calculated for each of the available abatement options. First the technical effectiveness of each option was calculated by multiplying the option's technical applicability by its market share by its reduction efficiency. This calculation yields the percentage of baseline emissions that can be reduced at the national or regional level by a given option. The technical effectiveness percentage was then multiplied by the applicable baseline emissions (MtCO₂e) to yield the emission reductions for the mitigation option.

$$\text{Technical Effectiveness (TE)} = TA \times MS \times RE \quad (4.1)$$

$$\text{Emissions Reductions (MtCO}_2\text{e)} = TE \times BE \quad (4.2)$$

Table 4-1: Calculation of Emission Reductions for an Abatement Option

Technical Applicability (%)	X	Market Share ^a (%)	X	Reduction Efficiency (%)	=	Technical Effectiveness (%)			
					Technical Effectiveness (%)	X	Baseline Emissions (MtCO ₂ e)	=	Emissions Reductions (MtCO ₂ e)
Percentage of total baseline emissions from a particular emission 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 emission abatement for an option after it is applied to a given emission stream.	Percentage of baseline emissions that can be reduced at the national or regional level by a given option.	Emission stream to which the option is applied.	Unit emission reductions.

^aImplied market shares for noncompeting mitigation options (i.e., only one option is applicable for an emission streams) sums to 100%.

where

TA = technical applicability (%)

MS = market share (%)

RE = reduction efficiency (%)

TE = technical efficiency (%)

BE = baseline emissions (MtCO₂e)

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. We used market shares for each mitigation option within every sector. The market shares, determined by various sector-specific methods, must sum to one for each sector and were assumed constant over time.⁶ This assumption avoids cumulative reductions of greater than 100% across options.

When nonoverlapping options are applied, they affect 100% 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 were applied independently to different parts of the sector and do not compete for the same emission stream.

⁶ For certain energy, waste, and agriculture sectors, accounting for adoption feasibility, such as social acceptance and alternative permutations in the sequencing of adoption, was outside the scope of this analysis.

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

Once the technical effectiveness of an option was calculated as described above, this percentage was 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 CO₂ equivalent (MtCO₂eq).⁷

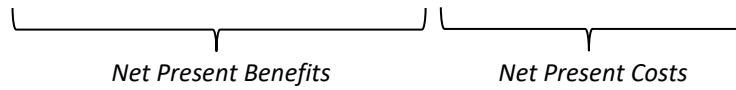
If the options were assumed to be technically feasible in a given region, they were assumed to be implemented immediately. Furthermore, once options are adopted, they were assumed to remain in place for the duration of the analysis, and an option's parameters do not change over its lifetime.

4.1.2 Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated unit of gas (tCO₂eq or tons of emitted gas [e.g., tCH₄]). The benefits include a carbon value/price expressed as \$/tCO₂e. The carbon price at which an option's benefits equal the costs is referred to as the option's break-even price.

For each mitigation option, the carbon price (P) at which that option becomes economically viable was 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 was used to determine break-even abatement costs in a given region. Break-even 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 break-even price P by equating the present value of the benefits with the present value of the costs of the mitigation option. More specifically,

$$\sum_{t=1}^T \left[\frac{(1-TR)(P \cdot ER + R) + TB}{(1+DR)^t} \right] = CC + \sum_{t=1}^T \left[\frac{(1-TR)RC}{(1+DR)^t} \right] \quad (4.3)$$



where

- P = the break-even price of the option (\$/tCO₂e)
- ER = the emission reduction achieved by the technology (MtCO₂e)
- 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 (%)
- 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 (%)
- TB = annual tax benefit of depreciation = $\left(\frac{CC}{T}\right) \cdot TR$

⁷ One MtCO₂eq equals 1 teragram of CO₂ equivalent (TgCO₂eq); 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

Assuming that the emission 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 break-even price P of the option for a given year:

$$P = \frac{CC}{(1-TR) \cdot ER \cdot \sum_{t=1}^T \frac{1}{(1+DR)^t}} + \frac{RC}{ER} - \frac{R}{ER} - \frac{CC}{ER \cdot T} \cdot \frac{TR}{(1-TR)} \quad (4.4)$$

Costs include capital or one-time costs and 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 CH₄ either as natural gas or as electricity/heat, the value of HFC-134a as a refrigerant), (2) non-GHG 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 GHG price in terms of dollars per tCO₂ eq (\$/tCO₂eq) or dollars per metric ton of gas (e.g., \$/tCH₄, \$/tHFC-134a). In most cases, the abatement of CH₄ has two price signals: one price based on CH₄'s value as energy (because natural gas is between 90% and 98% CH₄) and one price based on CH₄'s value as a GHG. All cost and benefit values are expressed in constant-year 2015 U.S. dollars. This analysis was conducted using a 5% discount rate and a 0% tax rate. For quick reference, Table 4-2 lists the basic financial assumptions used throughout this report.

Table 4-2: Financial Assumptions in Break-Even Price Calculations for Abatement Options

Economic Parameter	Assumption
Discount rate	5%
Tax rate	0%
Constant-year dollars	2017\$

4.1.3 International Adjustment Factors

Costs and benefits of abatement options were adjusted to reflect regional prices. Wages and prices vary by country. Hence, recurring O&M costs were segmented into labor, energy, and materials costs. Material cost components ranged from materials and supplies 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 were assumed to be relatively stable across regions and were 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 were generally assigned evenly as 33% each to labor, energy, and materials. For the agricultural sector, labor, energy, water, and other input costs were calculated from their shares of agricultural production costs based on social accounting matrix data from the Global Trade Analysis Project (GTAP) v8 database and agricultural wage data from the International Food Policy Research Institute (IFPRI).

In regions lacking detailed revenue (benefits) data, revenues were scaled based on the ratio between average prices of natural gas or of electricity in a given region and in the United States. We used the price of natural gas to value benefits when captured CH₄ is sold as natural gas, and we used the price of electricity to value benefits when the captured CH₄ is used to generate electricity or process heat. The natural gas and electricity prices used come from the Energy Information Agency's (EIA's) International Energy Statistics. Similarly, revenues from non-CH₄ benefits of abatement options were scaled based on the ratio between the gross domestic products (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 were combined with data on regional producer prices for the relevant agricultural commodity to calculate revenue changes.

Table 4-3 lists the international economic adjustment factors for selected countries. Using publicly available data on country-specific wage rates and energy prices, along with input from previous MAC analyses, we created indices reflecting each country's wage rates and prices relative to the United States. Adjustment factors were created for labor, natural gas, electricity, coal, and materials costs. When data were not available for a country, the country was either mapped to a similar country (with data) or previously developed Stanford Energy Modeling Forum (EMF) factors were used.

Table 4-3: 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 were obtained primarily from U.S. Bureau of Labor Statistics' (BLS's) International Labor Comparisons (2010a) and augmented with BLS (2010b, c) and Russian Federation Federal State Statistics Service (2010).

^b Energy prices were obtained from the EIA's International Energy Statistics (2010b).

^c Material factors were based on GDP/capita statistics obtained from the United Nations Conference on Trade and Development Statistical Database (2012).

Note that break-even price calculations for this analysis do not include transaction or monitoring and reporting costs, because this report contains no explicit assumptions about policies that would encourage and facilitate adoption of the mitigation options. Refer to Section 4.2.3 for a more complete discussion of the limitations of this analysis.

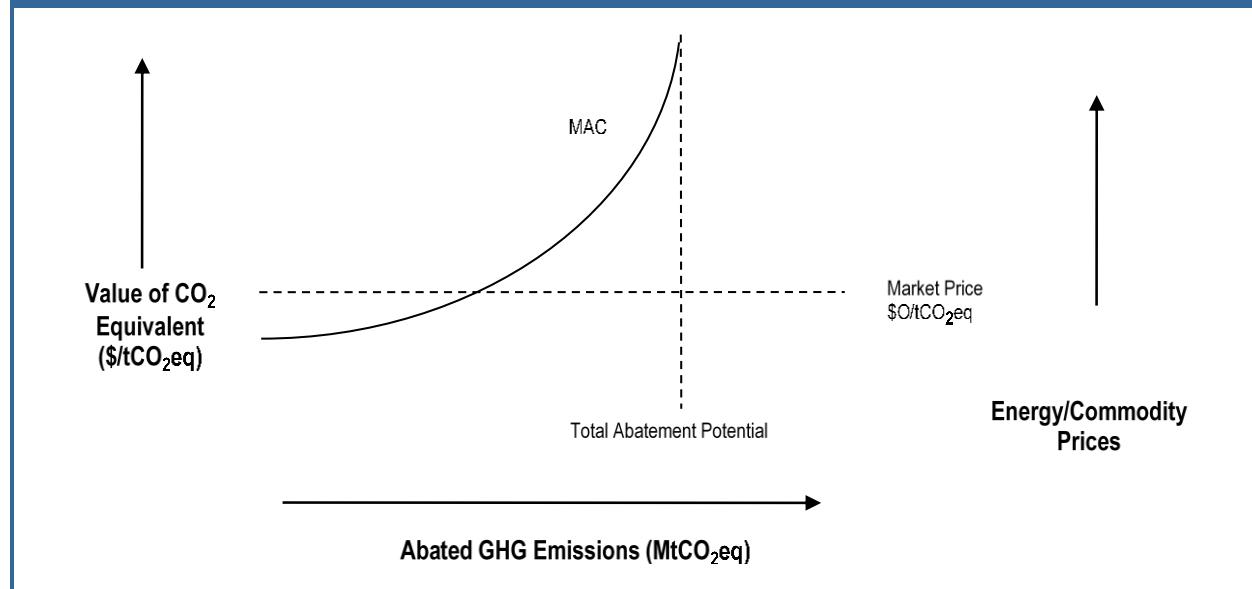
4.1.4 MAC Curves and Their Construction

MAC curves are used to show the amount of emission reduction potential at varying carbon price levels. In theory, a MAC curve illustrates the cost of abating each additional ton of emissions. Figure 4-1 shows an illustrative MAC curve. The x-axis shows the amount of emission abatement in MtCO₂eq, and the y-axis shows the break-even price in \$/tCO₂eq required to achieve the level of abatement. Therefore, moving along the curve from left to right, the lowest cost abatement options are adopted first.

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 emission reductions; any additional emission 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 curve that appear at or below the zero-cost line (\$0/tCO₂eq) 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, nonmonetary barriers may prevent their adoption.

Figure 4-1: Illustrative Non-CO₂ MAC Curve



The MAC curves in this report were constructed from bottom-up average break-even price calculations. The average break-even price was calculated for the estimated abatement potential for each mitigation option (see Section 3.3). The options were then ordered in ascending order of break-even price (cost) and plotted against abatement potential. The resulting MAC curve is a stepwise function, rather than a smooth curve, as seen in the illustrative MAC curve (Figure 4-1), because each point on the curve represents the break-even 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 MAC curves 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 break-even option price. In calculating the abatement potential, we evaluated options 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 were used to distribute adoption across the available options. In some instances, the lowest price option was selected for each representative facility. When limited information was available, the market share was evenly distributed (1/n) across all viable options. In this way, the implied adoption rate for each technology was estimated.

In the industrial processes sector, mitigation options were applied to representative facilities in order of lowest average break-even price to highest average break-even price. Each option was applied to a portion of the baseline emissions based on the implied adoption rate (the market share factor, as described in Section 3.2), which, in the industrial sector, was informed by expert insight into potential adoption rates of various mitigation technologies.

In the agriculture sector, mitigation options were applied to the portion of emissions where they are technically applicable (e.g., anaerobic digesters were assumed to be applicable only in intensively managed dairy and hog production systems). The implied market share for competing options was based purely on the number of available mitigation options (n) that are applicable to a given subset of emissions and that reduce emissions⁸ ($1/n$), where each option was 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 assumed 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%.

The MAC curves represent the average economic potential of mitigation technologies in that sector, because we 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 MAC curves 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 assumed partial equilibrium conditions that do not represent economic feedbacks from the input or output markets. This analysis made no assumptions regarding a policy environment that might encourage the implementation of mitigation options. Section 4.2.3 provides additional discussion of some key limitations of the methodology.

The end result of this analysis is a tabular dataset, available for download from the EPA website at <https://cfpub.epa.gov/nonco2/> for the MAC curves by sector, gas, and region.⁹

4.2 MAC Methodological Enhancements

This report builds on a study previously conducted by the EPA for Stanford's EMF-21 and the EPA (2006, 2013a) reports. As in previous MAC model updates, we have updated our economic cost for implementing mitigation options when new data were available, we incorporated the most recent set of international GHG emission projections and updated the baseline price forecasts and relative international adjustments factors for labor, energy, and materials.

Additionally, in this update to the MAC model, we introduced two major methodological enhancements that includes incorporating the effects of technology change on mitigation costs and their reduction efficiencies and

⁸ Some agricultural mitigation options may increase emissions under certain conditions depending on baseline regional management and soil, climate, and other considerations. In addition, many mitigation options increase emissions per head of livestock or per hectare of land but reduce emissions intensity per unit of output. Thus, agricultural MAC curves were calculated both assuming constant production and constant area/head of livestock to present a range of potential mitigation options. The options that provide net emissions reductions may differ between these alternative methods of MAC curve generation.

⁹ Tables are presented that provide the percentage abatement for a series of break-even prices. The MAC data are presented as tables so that exact values can be determined for use in modeling activities.

developing more regionalized sectoral MACs for the United States. The remainder of this section describes each of these enhancements in more detail.

4.2.1 Incorporating Technological Change

In this section, we describe the updated model’s integration of technological change using learning curves to model cost reductions resulting from accumulated experience, which is a well-established approach in the literature. Additionally, we describe two novel approaches for introducing more dynamic heterogeneity between countries within the model. Preliminary modeling results show that implementing technological change in the model results in an increase in the supply of emission reductions at a given price. This result is influenced by both, cumulative experience or learning overtime, and improved reduction efficiency associated with more nascent abatement measures.

4.2.1.1 Background

Using learning curves—also known as experience curves—to examine the relationship between cost and experience has been a tool since Wright (1936) first conceptualized “learning-by-doing” in the economics literature (Papineau, 2006). A learning curve tracks the reduction in cost of a technology, product, or service as a function of the accumulation of experience. The experience metric is a quantitative measure, usually cumulative, that is considered a proxy for learning. While cumulative production is the most common experience metric, others include installed generation capacity, cumulative production capacity, and average production facility size.

In the 1960s, Boston Consulting Group began to leverage the learning curve with consulting clients, and through the 1970s, it was primarily used as a strategic planning tool and production management tool (Papineau, 2006). Learning curves have been estimated for a wide variety of technologies, including chemical processing, airplane manufacturing, semiconductor production, and energy generation (Lieberman, 1984; Wright, 1936; Hatch and Mowery, 1998). More recently, learning curves have been widely leveraged to model technological change in climate change policy modeling, including in EIA’s National Energy Modeling System (Gillingham et al., 2008).

The learning curve is most commonly estimated using the following equations:

$$C_t = C_0 * X_t^\beta \quad (4.5)$$

$$LR = 1 - PR = 1 - 2^\beta \quad (4.6)$$

where C_t represents the unit cost of a technology in year t and C_0 represents the cost of the first unit of a technology when experience begins accumulating. X_t is the experience metric and β is a parameter measuring the responsiveness of cost to the experience metric. In Equation 5.6, LR is the learning rate, which can be interpreted as the percentage reduction in unit cost for every doubling of the experience metric. The progress rate (PR) is simply the inverse of the learning rate.

In addition to using the linear form of the learning curve equation (Equation 4.6), one can employ a log-log form of the learning curve or estimate a regression to test the statistical significance of multiple experience metrics at once. See Papineau (2006) or Gillingham et al. (2008) for more detailed exploration of the different approaches to estimating learning curves.

Broadly, researchers have also implemented technological change in modeling the MAC curve for non-CO₂ GHGs. Carrara and Marangoni (2013) estimated MAC curves and applied a technical progress factor that stretches the shape of the MAC curve to the right, simulating a larger share of abatement being captured at the same price as the carbon price relative to the MAC curve without technical change implemented. For this study, we borrowed from and expanded on the implementation of technological change in the Greenhouse Gas and Air Pollution

Interactions and Synergies (GAINS) model, which is an integrated assessment model used primarily in European climate modeling efforts (Höglund Isaksson et al., 2016). The GAINS model assumes a doubling rate of 15 years for the experience metric and a 15% learning rate. Additionally, Höglund Isaksson et al. (2016) also modeled technological progress by assuming an annual improvement in removal efficiency (RE) of 1%.

4.2.1.2 Operationalizing Technological Change

To operationalize technological change in the MAC curve model, we used the linear form of the learning curve equation (Equation 4.6) to project cost reductions over the study period of the model. To accomplish this, we had to specify the shape of an experience curve and then choose a learning rate. In an ideal scenario, historical data would inform both the shape of the experience curve and the learning rate; however, robust data were not available on rate of adoption and the cost trajectory of the abatement technologies in the model.

In the absence of better data, we specified a generic experience curve that we applied to all abatement technologies and we pulled from the literature to identify a reasonable learning rate based on studies of proxy technologies or industries. Additionally, as previously implemented in the GAINS model, we accounted for technological maturity and modeled modest improvements in RE (Höglund Isaksson et al., 2016).

4.2.1.3 Defining an Experience Curve

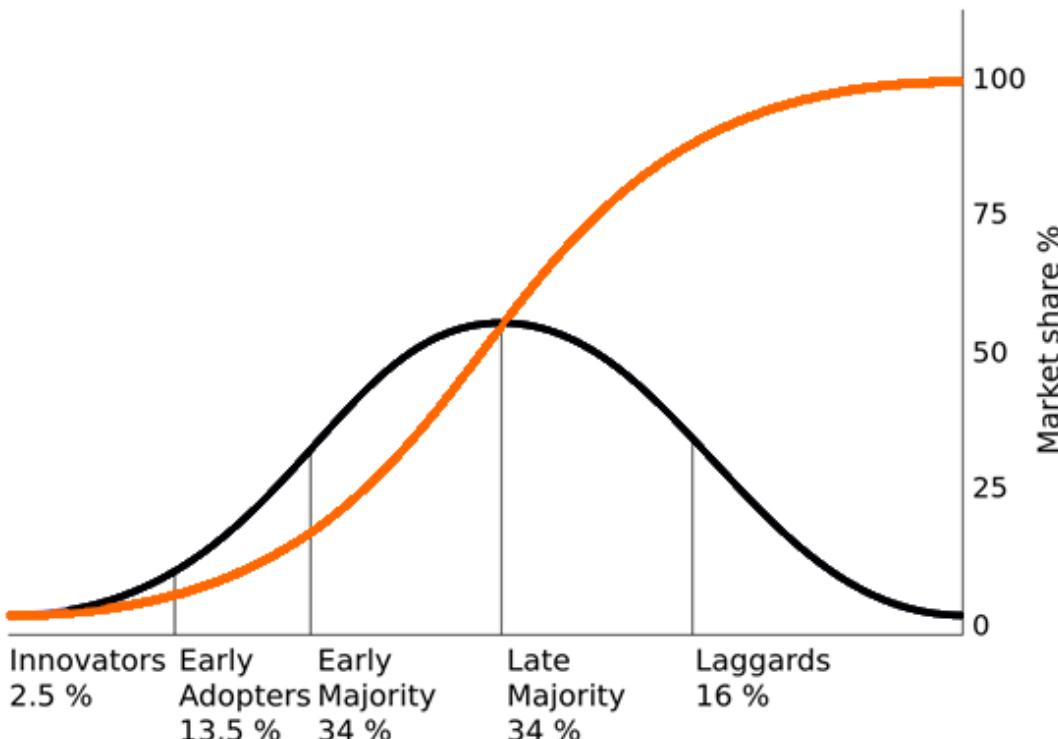
The rate of cost reductions when modeling technological change is not a function of time, but of experience. As described in the previous section, the learning rate is the percentage reduction in cost for every doubling of the experience metric, which is most often a cumulative production metric. Some applications in the learning curve literature assume a steady doubling rate. For example, the GAINS model assumes a doubling rate of 15 years in its implementation of technological change for non-CO₂ MAC curve estimation (Höglund Isaksson et al., 2016).

However, assuming a steady doubling rate builds in an assumption that the market for a product is limitless because growth over the long term becomes exponential. Rather than apply a steady doubling rate to the model, we drew from the innovation adoption literature to model a more realistic adoption path. Rogers (1962) was the first to propose the innovation adoption curve, which follows a sigmoidal shape, or an S-curve. Using a sigmoidal shape models a slower rate of adoption in the early years that accelerates as a product reaches a more mainstream audience. In the out-years, the adoption curve tapers off as the market becomes saturated. Figure 4-2, adapted from Rogers (1962), illustrates how different segments of adopters influence the pace of adoption and therefore the shape of the curve.

To operationalize this concept in the model, we used the general equation for a sigmoidal function (Equation 4.7), which gives us the flexibility to manipulate the shape of the curve by changing the asymptote (*max*), the slope of the curve (α), and the midpoint of the curve (*m*). Given the lack of data available on adoption trends for individual abatement technologies, we chose a conservatively sloped adoption curve with the primary focus being to model the slower pace of adoption at the tails of the curve (Figure 4-2).

$$\text{Sigmoidal curve equation: } X(t) = \frac{\max}{1+e^{-\alpha(t-m)}} \quad (4.7)$$

Figure 4-2: Different Segments of Adopters Influence the Pace of Adoption



Source: Adapted from Rogers, E. 1962. *Diffusion of Innovations*. London: Free Press.

4.2.1.4 Choosing a Learning Rate

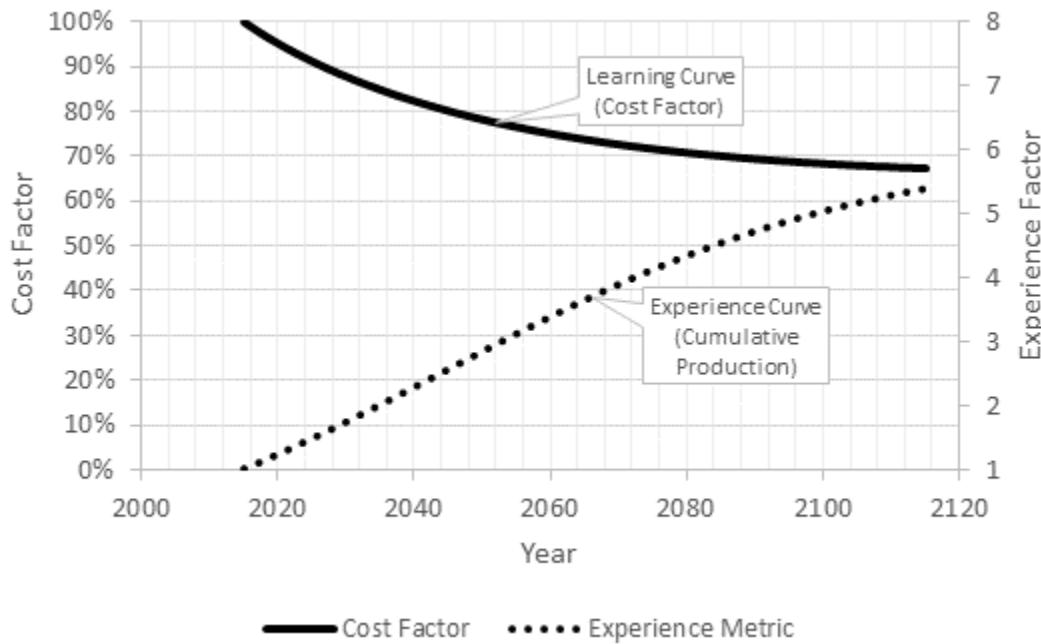
Once the experience curve is defined, we turn to choosing a learning rate. While many applications of the learning curve concept are directed to estimating the learning rate with real-world data about cost and adoption, the prospective nature of our modeling required choosing the learning rate in order to estimate the cost reduction.

In choosing a learning rate, we followed Höglund Isaksson et al.'s (2016) choice of 15%, which is grounded primarily in the literature that estimates learning rates for energy generation technology. Jamasb and Kohler (2007) reviewed the learning curve literature for energy technologies, citing 20% as a common “rule of thumb” learning rate. However, they argued that choosing 20% in a modeling setting may be optimistic if it is fixed over time because some evidence suggests that learning rates decline over the long term as further improvements become costlier and more difficult to achieve as low-hanging fruit is exhausted.

Höglund Isaksson et al. (2016) also argued that 20% may be unrealistic in the case of modeling more mature technologies for which many cost reductions have already been achieved. Thus, 15% is a conservative choice to account for the concern about overestimating cost reductions that are achievable over time.

Combining the experience curve and the learning rate yields a learning curve that drives costs down more rapidly in the early years and flattens out in later years as potential cost reduction opportunities are exhausted (Figure 4-3). The result of implementing the learning rate equation is a *cost factor* time series (C_t from Equation 4.5) that ranges from 0 to 1 and starts at 1 at the beginning of the learning curve. Thus, the cost factor can be interpreted as 100% minus the percentage reduction in cost achieved through learning. The cost factor is applied to the cost of an abatement technology to model cost reductions achieved over time through learning.

Figure 4-3: Illustrative Experience and Learning Curves



4.2.1.5 Accounting for Technological Maturity and Variation in Country Development Status

Limited data availability necessitates generalizing some of the implementation of technological change in the MAC curve model. For example, we used the same experience curve and the same learning rate across all abatement technologies. However, generalizing can be problematic—some distinctions can be made by taking into account the maturity of the abatement technology and the development stage of the country where the technology is being implemented.

As noted in the previous section, more mature technologies may have already achieved significant cost reductions prior to our study period. Applying the learning curve starting in the model base year could thus overestimate potential cost reductions for mature abatement technologies. To account for technological maturity, we classified each technology as either *nascent* or *mature*. The maturity level determines (1) when the technology starts down the learning curve within the model and (2) the assumed annual improvement in RE. For example, coalbed degasification technology is considered a mature technology because it has been widely used for worker safety for many years. Ventilation air methane (VAM) oxidation, while already commercialized, is not widely adopted and was thus classified as a nascent technology.

The development stage of a country may also affect the cost and pace of technological change. We assumed that emerging economies will not adopt abatement technologies as quickly and will face higher implementation costs because they may need to import foreign expertise in the earliest stages of technology adoption. To account for the development stage of countries, we classified each country as either *developed* or *emerging* based on their World Bank Income Group classification (World Bank, 2016). The development stage of the country also affects the year in which learning starts within the model. Table 4-4 presents the combined effect of technological maturity and economic development stage.

Table 4-4: Combined Effect of Technological Maturity and Economic Development Stage

Technology Status	Country		Annual Reduction Efficiency Improvement
	Developed	Emerging	
Nascent technology	2015	2020	1.0%
Mature technology	2000	2005	0.5%

Reduction Efficiency (RE) Improvements

As mentioned previously, technological change can also result in RE improvements independent of cost reductions. The GAINS model (2016a) assumes a 1% annual improvement in RE for non-CO₂ GHG abatement technology in their MAC curve models. We similarly assumed a 1% annual improvement in RE for nascent technologies but opted for a more conservative 0.5% annual improvement for mature technologies (Table 4-4).¹⁰ For the purposes of the model, we express RE in terms of an *emission factor*, which is represented by the percentage of a pollutant that is *not* captured after the abatement technology is implemented.¹¹

Nature of the Results

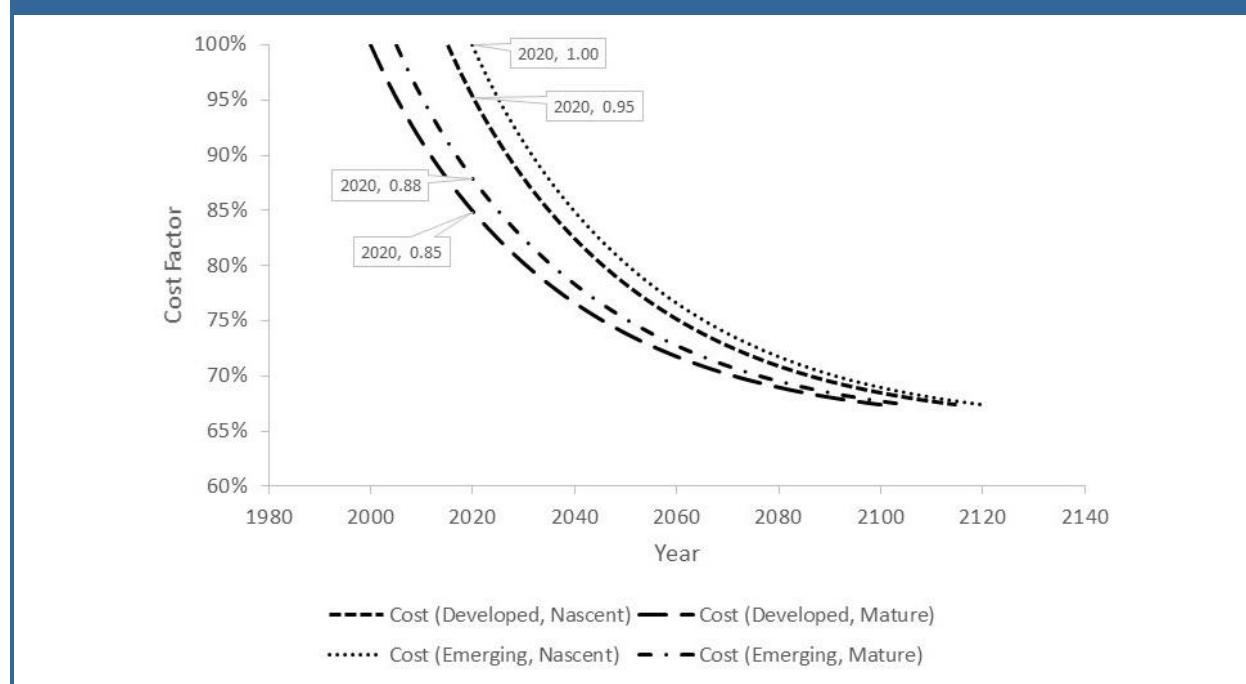
Accounting for technological maturity and economic development stage of a country yields a matrix of four cost factor and emission factor time series, which are presented in Table 4-5 to illustrate the interaction between the different parts of the learning curve implementation. While the emission factor trend varies depending on the maturity of the technology, the cost factor trend is uniform across the model, varying only when a technology starts to progress down the learning curve. Figure 4-4 graphically demonstrates the difference between the four maturity/development combinations. In 2020, mature technologies in developed nations are farthest along the learning curve, reflecting the assumption that abatement technologies are likely to be introduced in developed nations first.

Table 4-5: Cost Factor and Emission Factor Results

Year	Developed Nations				Emerging Nations			
	Nascent Technology		Mature Technology		Nascent Technology		Mature Technology	
	Cost Factor	Emission Factor	Cost Factor	Emission Factor	Cost Factor	Emission Factor	Cost Factor	Emission Factor
2015	1.00	1.00	0.88	0.93	1.00	1.00	0.91	0.95
2020	0.95	0.95	0.85	0.91	1.00	1.00	0.88	0.93
2025	0.91	0.90	0.82	0.88	0.95	0.95	0.85	0.91
2030	0.88	0.86	0.80	0.86	0.91	0.90	0.82	0.88
2035	0.85	0.82	0.78	0.84	0.88	0.86	0.80	0.86
2040	0.82	0.78	0.77	0.82	0.85	0.82	0.78	0.84
2045	0.80	0.74	0.75	0.80	0.82	0.78	0.77	0.82
2050	0.78	0.70	0.74	0.78	0.80	0.74	0.75	0.80

¹⁰ Note: A 1% improvement in RE is equivalent to $RE * 1.01$, *not* $RE + 1\%$.

¹¹ In other words, $EF = 1 - RE$.

Figure 4-4: Cost Factor by Year Based on Technological Maturity and Economic Development

4.2.1.6 Incorporating Dynamic Heterogeneity Across Countries

To estimate abatement costs outside of the United States, we scaled costs up or down using an adjustment factor based on the difference in GDP per capita between a given country and the United States. In previous versions of the model, this adjustment factor was static, which does not account for economic growth over time. Additionally, previous versions of the model assumed that each country faces its own domestic labor costs when implementing an abatement technology. In reality, we expect that an abatement technology would be more costly in countries that do not possess the necessary expertise domestically. Rather than facing their own domestic labor prices, the adopting country would face a higher foreign labor price until the expertise is internalized domestically.

Not accounting for economic growth over time, particularly in rapidly developing countries such as Brazil, India, and China, will have the effect of depressing projected abatement costs in the out-years of the model. Similarly, not accounting for the need to import foreign expertise when a new abatement technology is being introduced will also keep abatement costs lower than they should be in many countries, but in the early years of the model. The impact of lower abatement costs when not accounting for economic growth and foreign labor costs is that more abatement will be projected in the early years of the model than may be realistic. Incorporating these factors, on the other hand, results in a more conservative projection of abatement.

To account for economic growth and the time required to internalize expertise in an adopting country, we introduced two new features in the updated model. First, we modeled economic growth using projections of growth in labor and materials costs. To project labor cost growth, we used wage projections from the International Labor Organization (ILO), which we converted to 2015 Purchasing Power Parity (PPP) dollars (ILO, 2016; World Bank, 2017). Because of the limited country coverage, we aggregated countries based on World Bank Income Group classification and used a 5-year average growth rate. To project growth in materials cost, we used GDP per capita growth projections from the Shared Socioeconomic Pathways Scenario #2 (SSP2), which was drawn from the MESSAGE-GLOBIOM climate model (International Institute for Applied Systems Analysis [IIASA], 2016). GDP per

capita was also quantified in 2015 PPP dollars. Importantly, we did not use projections of actual wage cost or GDP per capita; instead, we used projected growth rates and applied those rates to 2015 wages and GDP per capita. Table 4-6 describes the data and data sources used in this part of the analysis.

Table 4-6: Data Sources for Projecting Economic Growth at the Country Level

Cost Category	Representative Metric	Units	Baseline Data Source	Growth Rate Projection Source
Labor	Projected wages ^a	2015 PPP dollars per hour ^b	International Labor Organization	International Labor Organization
Materials	GDP per capita	2015 PPP dollars per capita	IIASA SSP2, MESSAGE-GLOBIOM	IIASA SSP2, MESSAGE-GLOBIOM

^a Wages were projected using 5-year average growth rates based on World Bank Income Group classification.

^b PPP dollars were calculated using exchange rate data from the World Bank (2017).

Second, we modeled a *foreign-to-domestic labor shift* by imposing U.S. labor costs on foreign countries in the early years of the model and phasing them gradually to model the internalization of expertise within a country. The shift in labor costs was applied only to countries where labor costs are lower than in the United States. Other components of the cost of abatement—capital, energy, and materials—were assumed to follow the domestic costs in-country.

Economic growth projections and the foreign-to-domestic labor shift were operationalized by layering the two time series on top of the learning curve for each country. The result is a composite factor that can be applied to an abatement technology's cost to make it dynamic and responsive to country context over the study period of the model.

Figure 4-5 illustrates the impact of each enhancement of the model on the cost of an abatement technology. Figure 4-5A presents two learning curves, one for the United States (Base_{US}) and one for a hypothetical developing nation ($\text{Dev}_{\text{static}}$). These two curves represent a static relationship between the United States and another nation.

Figure 4-5B illustrates how $\text{Dev}_{\text{static}}$ changes when integrating a foreign-to-domestic labor shift as described previously. $\text{Dev}_{\text{LaborShift}}$ starts higher in early years because the nation is facing foreign labor costs in the early years of adopting an abatement technology. Over time, however, expertise is internalized in-country and labor costs merge with the original $\text{Dev}_{\text{static}}$ curve.

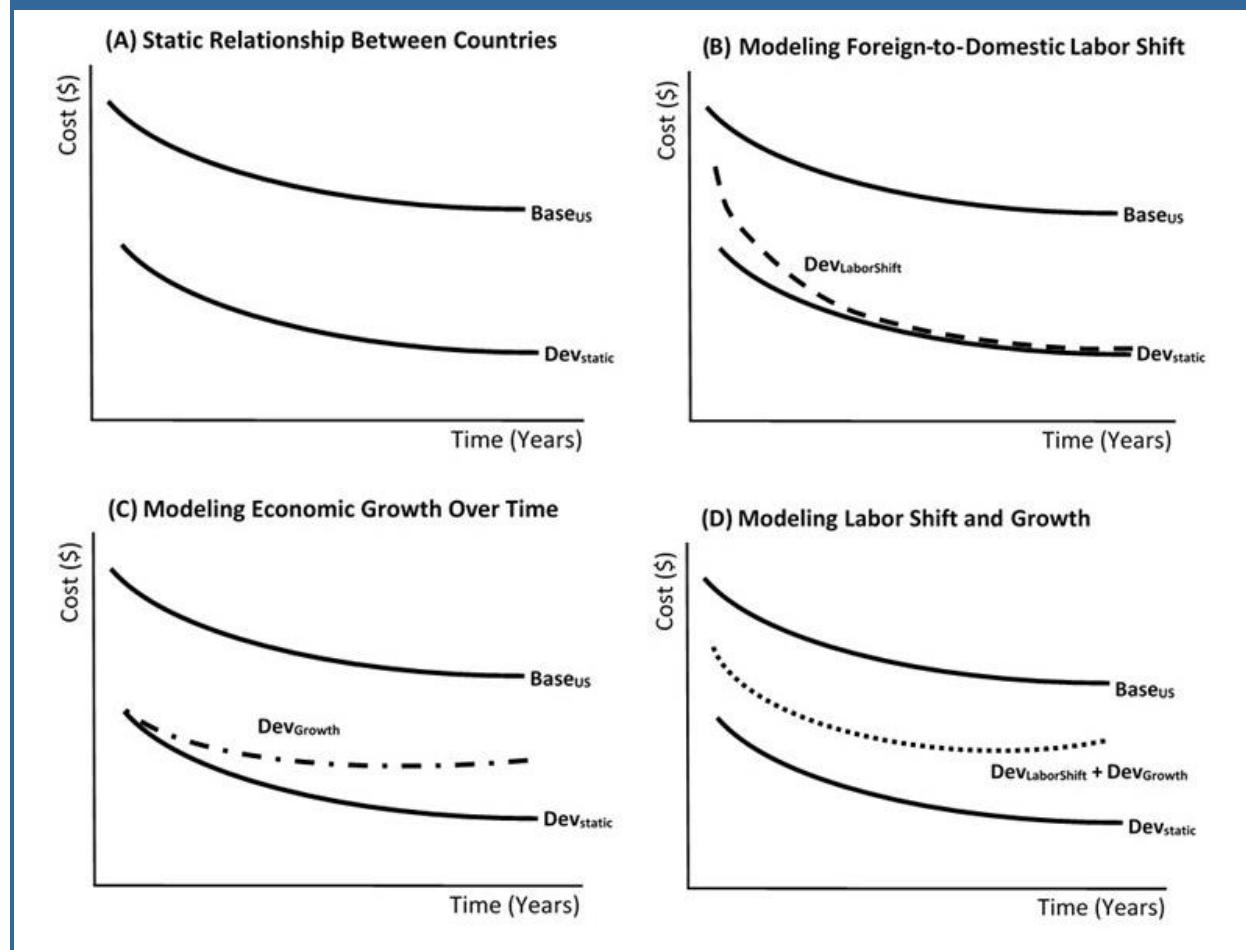
Figure 4-5C illustrates the impact on $\text{Dev}_{\text{static}}$ of modeling economic growth through increasing material and labor costs over time. In this illustrative example, $\text{Dev}_{\text{Growth}}$ shows that the hypothetical developing nation is experiencing a faster rate of economic growth than the United States, which causes the gap in costs between the two nations to close over time.

Finally, Figure 4-5D combines $\text{Dev}_{\text{LaborShift}}$ and $\text{Dev}_{\text{Growth}}$ to illustrate the combined effect of a labor shift and economic growth on $\text{Dev}_{\text{static}}$. It is important to reiterate that when modeling economic growth, we calculated relative factors for each country using the United States as the base. The Base_{US} curve, while it does not change throughout Figure 4-5, incorporates projections of the United States' own economic growth.

4.2.1.7 Integration into the Non-CO₂ MACC Model

The application of technology change to existing MACC calculations implies two important updates to the previous estimates. First, we switched from using static capital, labor energy, and materials (KLEM) factors as explained before, allowing them to change every year and representing the cost savings due to technological change. Second, by applying the RE improvement factor to the current technical effectiveness in the model, we introduced a dynamic reductions efficiency factor that improves over time.

Figure 4-5: Illustrative Example of the Impact of Modeling Foreign-to-Domestic Labor Shift and Economic Growth on Relative Cost Factors for Abatement Technologies



As described in Section 4.1, the MAC curve model characterizes each abatement option in terms of its costs and benefits per abated unit of gas (tCO₂e). Setting each option's benefits equal to costs, the MAC curve model solves for the carbon price (\$/tCO₂e), also referred to as the option's break-even price (Equation 4.8).

As shown in Equation 4.8, the adjustments to implementation costs affect the initial investment costs (CC) as well as the recurring costs (RC), while improvements to RE increase the quantity of GHG emissions captured (ER), and for energy-producing measures (captured and use of CH₄), the adjustment also affects the revenue (R) component.

$$P = \frac{CC_t}{1 - TR \cdot ER_t \cdot \sum_{t=1}^T \frac{1}{(1+DR)^t}} + \frac{RC_t}{ER_t} \cdot \frac{R}{ER_t} \left(\frac{CC_t}{ER_t \cdot T} \cdot \frac{TR}{1 - TR} \right)$$

CC_t Impacted by learning
 ER_t Impacted by removal efficiency improvement

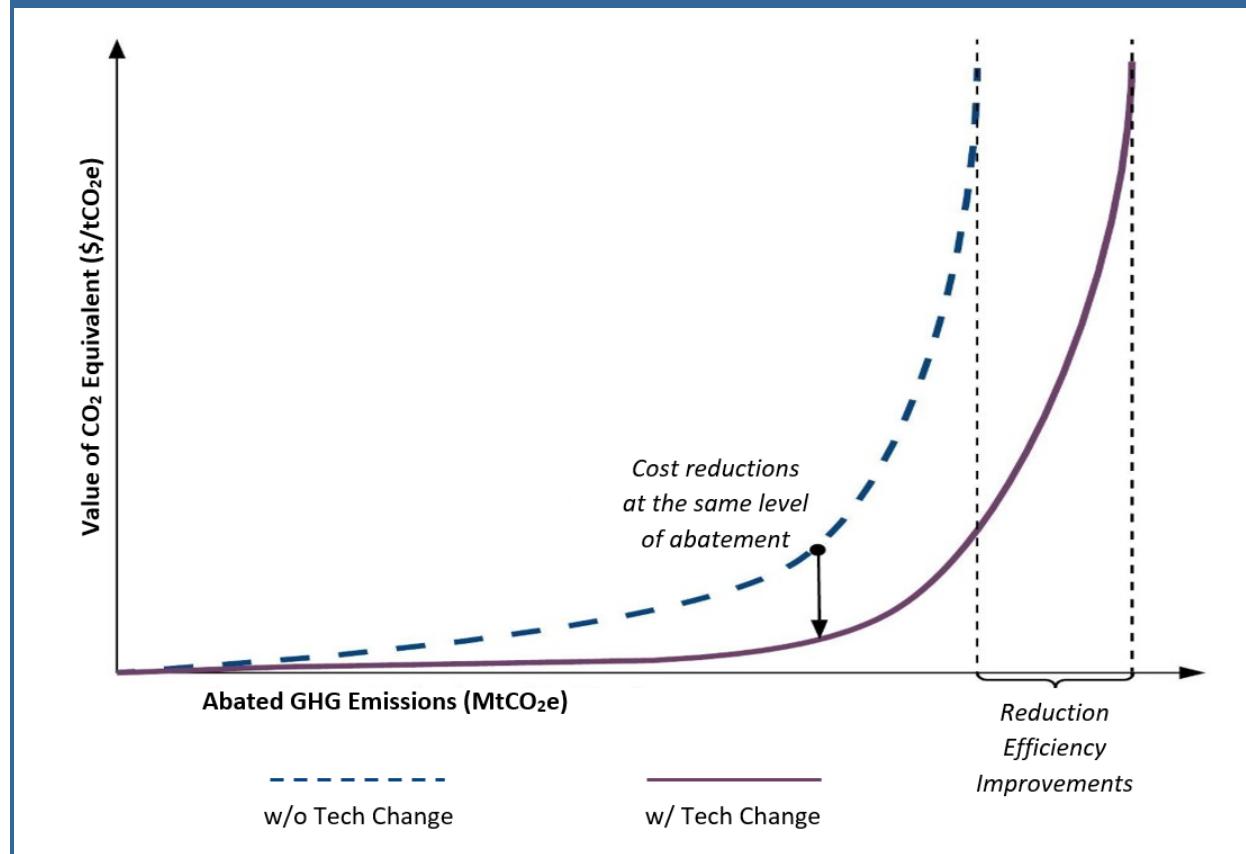
(4.8)

The break-even analysis yields the new adjusted break-even price and corresponding incremental emission reduction for each mitigation measure evaluated across 195 countries.

Operationalizing technological change in the MAC model has two general effects on the shape of the resulting MAC curve. Reduction efficiency improvements shift the asymptote of the MAC curve outward, increasing the maximum abatement potential of the technology. Cost reductions through learning yield the same level of abatement at a lower cost, causing a downward shift in parts of the MAC curve.

Figure 4-6 shows two illustrative MAC curves with and without technological change to demonstrate the effects of cost reductions and removal efficiency improvements. All other things being equal, the magnitude of the shifts in the MAC curve will be greater for emerging economies than for developed economies.

Figure 4-6: Illustration of Technology Change's Impact on a Non-CO₂ MAC Curve



4.2.2 Regionalization of Sectoral MAC Curves for the United States

The second major enhancement we have made to the MAC model since the global mitigation report (EPA, 2013a) was to develop regionalized sectoral MAC curves for the United States to better capture the heterogeneity in cost of mitigation and provide more explicit geospatial representation of the abatement potentials. These regionalized MAC curves now replace the single national MAC curve previously produced for the United States.

We have developed regional MAC curves for the coal mining, oil and gas, landfills, and nitric/adipic acid production; livestock; rice cultivation; and cropland soil management sectors. Requisite regional data for developing comparable regional MACs for the 12 industrial sources were not available at the time of this publication, but it is our goal to develop regional MAC curves for these sectors in future updates.

We used state-level data on production input costs (labor, energy, and materials), yields, and emission factors to derive regional MAC curves for the United States. This detailed modeling framework enables us to calculate the

quantity of GHG reductions and corresponding mitigation costs at the state and regional levels to introduce more heterogeneity into the MAC model. The methods and approach used are similar to those developed for a study regionalizing the domestic MAC curves for four U.S. non-CO₂ emitting sectors that included coal mining, oil and gas, landfills, and nitric/adipic acid production (Rose, Petrusa, and Davis, 2013).

GHG abatement was quantified by technology for each state and can be aggregated to larger regions for simplified reporting results. The suite of mitigation options evaluated in the regional models is consistent with the international model. The state-level supply of GHG mitigation for each source was developed following a common four-step approach.

First, we derived state-level baseline GHG emissions based on the regional share of activity or production. For example, in coal mining, we used the underground coal mining production to estimate the share of emissions by state. For the agricultural sectors, we used the state shares of national production to determine state-level baselines for livestock and rice cultivation. Second, we estimated the direct costs and benefits of state-level GHG mitigation. We then used the state-level baselines and mitigation measure economics to calculate break-even prices associated with adopting each mitigation measure in each state. Finally, we constructed MAC curves for each state in the contiguous United States (Alaska and Hawaii were omitted for this analysis).

4.2.2.1 Specification of Baseline GHG Emissions by Region and Sector

For each sector, we developed state baseline production levels and GHG emissions for the years 2015 through 2050. This initial step defined the pool of GHG emissions and the quantity of emissions applicable to each mitigation measure. The data sources used to generate state baseline emissions varied across the three source models. For livestock, we developed state-level baseline activity based on head counts by animal type reported by the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (2014a, b, c). Additionally, we used data from the EPA 2016 GHG Inventory to develop state-level shares of baseline emissions and relative emission factors by animal type.

For rice cultivation, we relied on the DNDC model to determine regional production and emissions resulting from various irrigation and nitrogen use regimes to derive the resulting GHG emissions by state. Emissions are available at a national level from DNDC and are allocated to rice-producing states (Arkansas, California, Louisiana, Mississippi, Missouri, and Texas for our analysis) using state-level rice production shares and area data. More information about the DNDC data can be found in the 2013 mitigation report (EPA, 2013a).

For nonrice croplands, we relied on spatially disaggregated data from the DAYCENT model, including crop production areas and emission rates. The DAYCENT model results are provided on a 25-km grid cell basis for North America. We calculated weights based on grid area to allocate shares of harvested area, yields, and GHG emissions (CH₄, N₂O, and soil carbon) to each state in the contiguous United States.

4.2.2.2 Regional Price Adjustment Factors (KLEM)

We developed state-specific mitigation costs (initial capital investment, annual recurring fixed and variable O&M) and benefits (e.g., labor savings, energy savings, yield impacts). Accounting for regional differentiation in prices for labor, energy, and materials allowed us to create heterogeneity in the break-even prices across states for the same mitigation technology. We developed state price factors using deviations from national average prices for capital, labor, electricity, and materials. Here, the state price factor represents the ratio of state price to national average price. Table 4-7 provides summary statistics on the relative price factors calculated across states.

Table 4-7: Regionalized Price Adjustments Factors, Descriptive Statistics

Price Factor	Minimum	Maximum	Median	Mean	Standard Deviation
Labor^a					
Non-ag sectors	0.24	4.30	1.00	1.08	0.52
Cattle	0.77	1.07	0.98	0.97	0.07
Dairy cattle	0.62	1.30	1.00	1.04	0.16
Swine	0.62	1.30	1.00	1.04	0.16
Maize	0.81	1.43	1.07	1.10	0.15
Soy	0.41	3.41	0.81	0.96	0.63
Sorghum	0.34	3.36	1.00	1.15	0.63
Wheat	0.65	4.30	1.04	1.37	0.89
Barley	0.24	2.63	1.00	0.93	0.57
Rice	0.66	1.31	1.00	0.99	0.08
Electricity^b					
All sectors	0.61	4.12	0.96	1.14	0.55
Materials^c					
Non-ag sectors	0.72	1.90	1.00	1.02	0.12
Cattle	0.79	1.24	1.01	1.02	0.08
Dairy cattle	0.87	1.14	1.00	1.01	0.05
Swine	0.87	1.14	1.00	1.01	0.05
Maize	0.84	1.30	0.98	1.01	0.11
Soy	0.83	1.35	1.00	1.03	0.13
Sorghum	0.86	1.07	1.00	1.00	0.04
Wheat	0.84	1.72	1.00	1.04	0.21
Barley	0.72	1.50	1.02	1.07	0.15
Rice	0.74	1.90	1.00	1.01	0.14

Sources: ^a [Non-ag sectors] U.S. Bureau of Labor Statistics (BLS). 2018. Annual Mean Wage: Construction and Extraction Occupations (SOC code 470000); [Agriculture sectors] USDA Economic Research Service (ERS). 2018. Production Costs and Returns Data by Commodity.

^b U.S. Energy Information Administration. 2017. State Energy Data System (SEDS).

^c [Non-ag sectors] U.S. Bureau of Economic Analysis. 2018. Gross Domestic Product per Capital by State; [Agriculture sectors] U.S. Department of Agriculture, Economic Research Service. 2018. Production Costs and Returns Data by Commodity.

To be consistent with the international MAC curve modeling, we assumed that there is no regional differentiation in capital costs. Hence, the relative cost factor for capital is 1 in all states.

Labor and materials factors were constructed using the Commodity Costs and Returns reports from USDA's Economic Research Service (USDA, 2018) for the specific crops and livestock types included in the model. Data were available at the USDA Farm Resource Region level. These data were mapped to states using a county-to-

Resource Region mapping from USDA.¹² Materials cost indices were constructed using components of operating costs detailed in the commodity costs and returns report that were not already accounted for in the model (e.g., custom operations, repairs, irrigation, or other variable expenses) relative to U.S. values. Relative costs of inputs like seeds, fertilizer, fuel, or chemicals were not included in these materials cost indices because the model already accounts for them. The term “materials” is intended to capture all the nonlabor and nonenergy recurring O&M costs or potential savings associated with each mitigation measure.

Labor cost indices were calculated using regional hired labor costs as reported in the USDA Commodity Costs and Returns report relative to U.S. values. These relative costs were allocated to states using an average weighted by the area of the state in each Resource Region.

Electricity factors were calculated based on industrial sector electricity prices reported by EIA’s State Energy Data System (2016) from 2010 to 2014. These prices were averaged by state and divided by the U.S. 5-year average from that period to calculate a state price factor for electricity. We used this price factor to adjust any recurring energy costs for operating a mitigation technology as well as the potential revenue associated with electricity offsets resulting from converting captured CH₄ to electricity.

It is important to note that these price factors are static in our analysis. While we allow real price growth for the national price over time, the relative cost across states does not change.

4.2.3 MAC Limitations and Uncertainties

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

Exclusion of Transaction Costs

Ongoing work in the area of mitigation costs continues to focus on including transaction costs. As discussed in the 2007 version of this report, *Assessing Transaction Costs of Project-based Greenhouse Gas Emissions Trading* (Antinori and Sathaye, 2007), transaction costs range between \$0.03 per metric ton of CO₂ for large projects and \$4.05 per metric ton of CO₂ for smaller projects, with a weighted average of \$0.36 per metric ton of CO₂ for a suite of projects considered. More recent MAC work by others (Rose et al., 2013) estimated that 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.

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 sections. 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. The applicability of abatement options, for example, relies 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 on CH₄ abatement in countries outside the United States and EU. Incorporating more regional data could also enhance the range of emission sources and mitigation options addressed in this analysis.

¹² USDA Farm Resource Regions were mapped to counties using this mapping: <https://wayback.archive-it.org/5923/20110913212900/http://www.ers.usda.gov/Briefing/ARMS/resourceregions/resourceregions.htm> ↗.

Exclusion of Indirect Emission Reductions

This analysis does not account for indirect emission reductions, which can result from either the substitution of electricity from the grid with electricity produced on site from recovered CH₄ or from the substitution of natural gas in pipelines with recovered CH₄. 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 emission reductions by about 15%. In the agricultural sector, although some mitigation options primarily target a single gas, implementation of the mitigation options will have multiple GHG effects, most of which are reflected in the agricultural results.

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5 Sector-Level Methods

This section describes the source-specific methodology, organized by the four sectors—energy, industrial processes, agriculture, and waste. Within each sector, information on the activity data and emission factors used for both historical and projected emission estimates and the mitigation options considered is provided for each source category. Assumptions, data sources, and calculations are described along with a concluding section that identifies the uncertainties and other considerations associated with developing the emission and mitigation estimates.

5.1 Energy Sector

This section presents the methodology used to estimate CH₄ and N₂O emissions and mitigation from the following energy sources:

- coal mining activities (CH₄) (projections and mitigation)
- ONG systems (CH₄) (projections and mitigation)
- stationary and mobile combustion (CH₄, N₂O) (projections only)
- biomass combustion (CH₄, N₂O) (projections only)
- other energy sources (CH₄, N₂O) (projections only), including
 - waste incineration (CH₄, N₂O) and
 - fugitives from solid fuels (N₂O)

5.1.1 CH₄ in Coal Mining

CH₄ is stored within the coal seams and the surrounding rock strata and is liberated when the pressure above or surrounding the coal bed is reduced as a result of natural erosions, faulting, or mining. CH₄ is produced during the process of coalification, where vegetation is converted by geological and biological forces into coal. Because CH₄ is explosive, the gas must be removed from underground mines high in CH₄ as a safety precaution.

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 important resource through underground and surface mining releases CH₄ stored in the coal bed and surrounding geologic strata.

The quantity of gas emitted from mining operations is a function of two primary factors: coal rank and coal depth. Coal rank is a measure of the carbon content of the coal, with higher coal ranks corresponding to higher carbon content and generally higher CH₄ content. Coals such as anthracite and semi anthracite have the highest coal ranks, while peat and lignite have the lowest. Pressure increases with depth and prevents CH₄ from migrating to the surface; as a result, underground mining operations typically emit more CH₄ than surface mining. In addition to emissions from underground and surface mines, post-mining processing of coal and abandoned mines also release CH₄. Abandoned coal mine emissions are included in the Other Energy source estimates.

5.1.1.1 Coal Mining Projections Methodology

Estimates consist of CH₄ emissions from surface and underground mining. UNFCCC-reported, country-specific estimates were used to give historic emission estimates and to determine emission rates of projections. The methodologies described in this section were used to determine trends over time, or if country-reported emission estimates were not available for any historical years, EPA used the 2006 IPCC Tier 1 methodology (IPCC, 2006) to estimate emissions (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for coal mining included anthracite, metallurgical, bituminous, subbituminous, and lignite coal

production and consumption from EIA (2018). Projections of consumption data were also provided by EIA (2018). As China is the top coal-producing country, a country-specific methodology was used to estimate China-specific emission estimates. Emissions from coal mining were disaggregated into surface and underground mining. EPA also accounted for CH₄ abated by coal mine CH₄ projects as reported in the EPA International Coal Mine Methane Projects Database. The Tier 1 basic equation to estimate CH₄ emissions from coal mining is as follows:

$$\text{Fugitive CH}_4 \text{ Emissions} = (\text{Annual Lignite Production} \times EF_{\text{SURFACE}}) + (\text{Annual Other Coal Production} \times EF_{\text{UNDERGROUND}})$$

Unless otherwise noted, the EPA assumed that lignite is produced at surface coal mines, while other coal is produced in underground mines. Because a default methodology for fugitive emissions from abandoned mines is not currently available, this source is not considered in this report, unless it is included in country-reported emissions.

Activity Data

Historical

Because China is the top coal-producing country, a country-specific methodology was used to estimate China-specific emission estimates. A presentation given by the China Coal Research Institute (Lixin, 2016) provides detailed estimates of China-specific emissions by production type (surface versus underground) and from different stages of production (VAM, mining, and post-mining). Based on the presentation, a China-specific net emission value was obtained for 2015. This 2015 net emission estimate was used in conjunction with UNFCCC country-reported 1994 and 2005 values to calculate historical emissions. To interpolate the years between each of these country-specific estimates, a GHG intensity was determined using the country-reported estimates and EIA-reported production volumes for the 3 years 1994, 2005, and 2015. These intensities for each year were then interpolated and multiplied by that year's associated EIA production volume to give revised net emission estimates for China.

For all other countries, when UNFCCC country-reported data were not available for any years, historical emissions were calculated using the Tier 1 equation above and activity data and emission factors as outlined below.

- Coal production estimates for total primary production, hard coal production, and lignite production for 1990 through 2014 were obtained from EIA's International Energy Statistics Portal (EIA, 2018).
- Production estimates were disaggregated into surface and underground mines, assuming that hard coal is produced in underground mines and lignite, or soft coal, is produced in surface mines. While total primary coal production is available for all historic years, the EIA-reported data provide production volumes by type of coal for 2013 and 2014 only. Therefore, surface and underground proportions of production from 2013 were chosen to apportion primary coal production into surface and underground volumes for all historic years.
- If historical data were unavailable for a particular country through the UNFCCC or EIA's International Energy Statistics Portal, it was assumed that coal mining emissions were zero.

Projected

Activity data were forecasted using projected changes in country-level coal consumption from EIA's *International Energy Outlook* (EIA, 2017). If EIA did not report country-specific coal consumption forecasts, EIA's trend estimates for the country's region were used. In some cases, EIA provided estimates for a few countries within a region and then an estimate for the "rest of" the region. For applicable countries, "rest of" estimates of forecasted coal consumption were used to project activity data.

Emission Factors

Historical and Projected

Where IPCC Tier 1 methodology was used, CH₄ emissions from coal mining activities were determined by multiplying activity data (i.e., soft and hard coal production) by default Tier 1 IPCC emission factors from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). The *2006 IPCC Guidelines* provide low, average, and high Tier 1 emission factors. The average emission factor was used for each country-level estimate.

Emission Reductions in Baseline Scenario

The EPA considered accounting for CH₄ abated by coal mine CH₄ projects as reported by those projects in the EPA International Coal Mine Methane Projects Database. However, emission estimates were not adjusted for any country that self-reported estimates in UNFCCC. It was assumed that countries that self-reported estimates had the opportunity to account for coal mine CH₄ projects in their own estimates and that any country-made adjustments for coal mine CH₄ projects were captured when projecting emissions forward; however, whether countries actually accounted for coal mine CH₄ projects in their estimates is unknown.

For countries that did not self-report estimates, China, Mexico, and South Africa were the only three countries that have reported reductions that were considered. Of those countries:

- China: country-specific methodology, as discussed above, inherently includes reductions.
- Mexico and South Africa: coal mine recovery-reported reduction volumes are low in magnitude and have little impact on results.

Based on these criteria, country-level estimates were not adjusted for reported reductions.

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

Several methodologies were used to calculate historical emissions, depending on data availability for a given country. While this approach generated more detailed estimates than under a general, one-size-fits-all approach, it introduces some uncertainty to the estimates.

Emissions were projected using regional coal consumption growth rates and, for the most part, were not customized to individual countries. While this approach allows regional trends to be consistent with trends projected by EIA, it introduces uncertainty into emissions for individual countries.

Furthermore, emission estimates were calculated by projecting aggregated total coal consumption rather than calculating emissions based on trends of underground and surface mining using the Tier 1 equation. This approach introduces uncertainty because it would not capture any shifts in surface to underground mining (or vice versa), which are associated with different emission factors.

Emission calculations for this source were based on coal production and consumption statistics, divided into hard coal and lignite. Classes of coal are often difficult to determine; therefore, production estimates themselves can contain uncertainties. Additionally, CH₄ emissions are not necessarily directly related to production. CH₄ emissions occur not only during mining, but also during the pre-mining stage and after mining is completed. In addition, the actual gas levels of a mine can vary significantly based on geologic factors. More accurate estimation would include information on the gas levels of mines in particular regions and mine operations in the pre-mining and post-mining stages.

5.1.1.2 *Mitigation Options Considered*

Five abatement measures were considered for underground coal mining: pipeline injection, on-site electricity generation, on-site use for process heat, enclosed flare system, and VAM oxidation. We classified the five abatement measures into three technology categories: energy end uses, excess gas flaring, and mitigation of VAM. It should be noted that mitigation of gas from degasification systems and mitigation of gas from 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 CH₄ 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 VAM recovery or mitigation system (where applicable). Table 5-1 summarizes the five mitigation technologies analyzed.

Table 5-1: 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%

^aCapital costs include costs of both recovery and abatement equipment requirements.

^bAbatement potential expresses the maximum potential emission reductions at a facility level.

The components of the capital and annual costs for the drainage wells are outlined as given in the EPA's CMOP Cash Flow Model documentation (EPA, 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 was included in the costs of all abatement measures with the exception of VAM oxidation.¹³ 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 CH₄ end-use technology. The total installed capital costs vary by location and gas flow rate. For example, assuming a 600 Mcf/day volume of CMM gas (with a CH₄ concentration of 90%), we estimate the capital costs would be \$850,000.
- **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

¹³ 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.

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%.

Energy End Uses

High-quality CH₄ 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 (EPA, 2011b).

Pipeline Injection

Natural gas companies may purchase CH₄ recovered from coal mines. CH₄ 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% CO₂ or nitrogen and 1 ppm oxygen. Although CH₄ 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 CH₄ also can be obtained from gob wells.

Pre-mining degas wells are the preferred recovery method for producing pipeline-quality CH₄ from coal seams because the recovered CH₄ 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 CH₄ is frequently mixed with ventilation air. Gob gas CH₄ 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 (EPA, 2008).

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 affects 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 (EPA, 2008). 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 EPA (2011b), include the installation of a pressure swing adsorption system to remove nitrogen and CO₂ down to a 4% inert level. The utilization cost is a function of both the inlet gas flow rate and CH₄ 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. Although pipelines operate at a range of pressures, this analysis assumed 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 were 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 assumed a technical effectiveness of 21%. As shown in Table 5-2, this technical effectiveness considers a recovery efficiency of 75% (reflects the loss of 25% of the gas that cannot be used in pipeline injection because the CH₄ concentration is too low to process to pipeline specifications) and a 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

Table 5-2: Factors Used to Estimate Abatement Potential in Coal Mines

Abatement Measure	Facility Applicability	Technical Feasibility	Reduction Efficiency	Technical Effectiveness
Energy End Uses: Drained Gas^a				
Pipeline injection	100%	100%	75%	28%
On-site electricity generation	100%	100%	75%	28%
On-site direct use	100%	100%	75%	28%
Mitigation Only: Drained Gas^a				
Enclosed flare system	100%	100%	75%	28%
Oxidation of VAM^a				
VAM oxidation	100%	77%	25%–90%	19–68%

^a Drained gas is assumed to represent 32% of a facility's annual emissions, while VAM represents the 68% of annual emissions.

On-Site Electricity Generation

Drained CH₄ can be used to fire internal combustion (IC) engines that drive generators to make electricity for sale to the local power grid (EPA, 2011b). The quality of CH₄ required for use in power generation can be less than that required for pipeline injection. IC engine generators can generate electricity using gas that has heat content as low as 300 Btu/cf or about 30% CH₄. Mines can use electricity generated from recovered CH₄ to meet their own on-site electricity requirements and can also sell electricity generated in excess of on-site needs to utilities (EPA, 2008).

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 (EPA, 2008).

- **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 were 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 U.S. dollars.
- **Annual Benefits:** Offsets or cost savings associated with power that would have otherwise been purchased at market electricity prices represent the annual benefits for this option. 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/kWh¹⁴, this project would generate \$1.2 million in revenue from electricity sales.

- **Technical Effectiveness:** The analysis assumed 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

On-Site Use for 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 CH₄ 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 CH₄ and that the drained CH₄ 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 million British thermal units per hour (MMBTU/hr) 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 CH₄ 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 assumed 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 collocated near an underground mine. The existing coal drying process can be retrofitted to burn CH₄ 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 (EPA, 1998). Assuming the average coal dryer heating requirement is 228 MMBTU/hr, 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.

¹⁴ The actual price utilities would be willing to pay will vary depending on the 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/kWh in the United States.

- **Annual Benefits:** Benefits are the energy costs offset by using the drained CH₄ 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 used a technical effectiveness of 28%, which assumes a recovery efficiency of 75% and destruction efficiency of 98% when combusted in the mine boiler.
- **Technical Lifetime:** 15 years

Excess Gas Flaring

After recovering CH₄ using the drainage well technique, mines can choose to flare CH₄ of greater than 30% concentration (EPA, 2011a). Flare systems considered include an open flare and an enclosed combustion system, which consist 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 CH₄ 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 were 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:** No revenues were associated with this option.
- **Technical Effectiveness:** The analysis used a technical effectiveness of 28%, which assumes a recovery efficiency of 75% and destruction efficiency of 98% when combusted in a flaring system.
- **Technical Lifetime:** 15 years

Mitigation of VAM

Oxidation technologies (both thermal and catalytic) have the potential to use CH₄ emitted from coal mine ventilation air. Extremely low CH₄ 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 H₂O and CO₂. VAM oxidation is technically feasible at CH₄ 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.

- **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 CH₄ 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 assumed this abatement measure has no energy-related benefits.
- **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

Table 5-2 provides the specific factors used to calculate the technical effectiveness parameter for each abatement measure in the coal mining sector. As discussed in Section 3, the technical effectiveness is the product of facility applicability, technical feasibility, and reduction efficiency.

5.1.1.3 Sector-Level Trends/Considerations

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: (1) the equipment itself is large and costly; (2) there is no 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 UNFCCC's Clean Development Mechanism (CDM) or the EU's Emissions 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 section were assumed to be mature technologies.

5.1.1.4 References

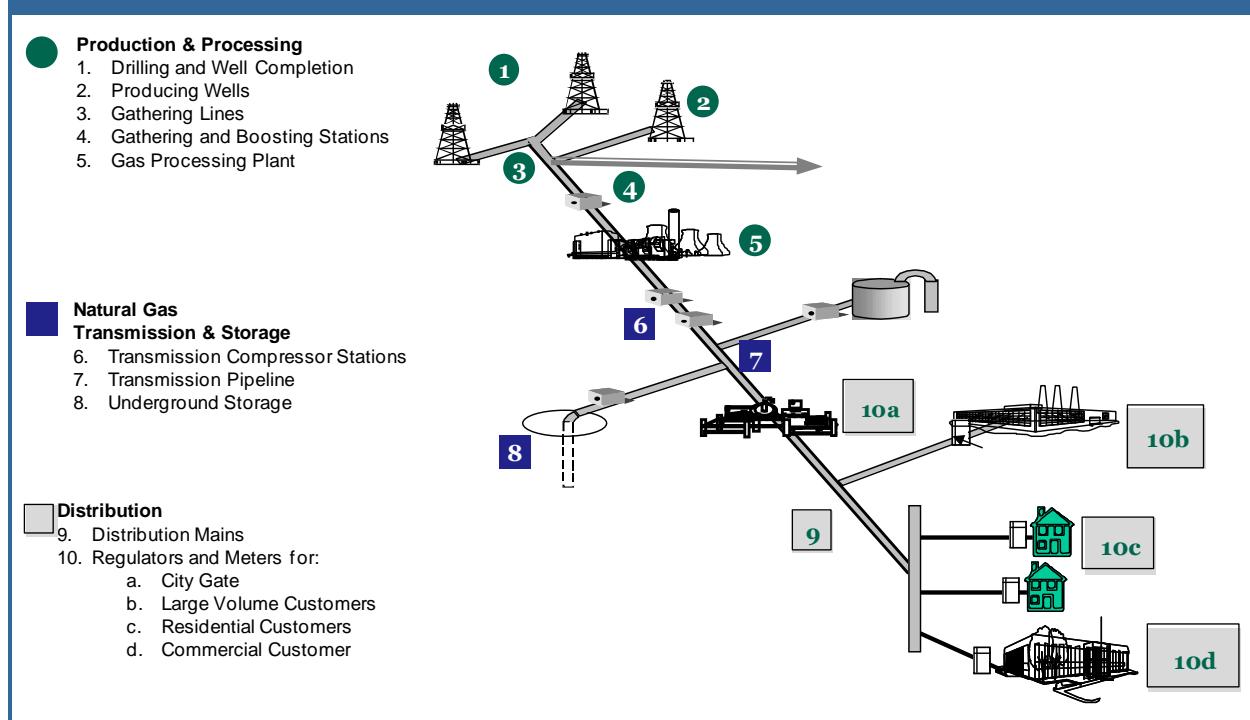
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5.1.2 Oil and Natural Gas Systems

Methane, or CH₄, is the principal component of natural gas (95% of pipeline quality natural gas) and is emitted from natural gas production, processing, transmission, and distribution. Oil production and processing upstream of oil refineries can also emit CH₄ in significant quantities because natural gas is often found in conjunction with petroleum deposits. In both ONG systems, CH₄ is a fugitive emission from leaking equipment, system upsets, and deliberate flaring and venting at production fields, processing facilities, natural gas transmission lines and compressor stations, natural gas storage facilities, and natural gas distribution lines. Figure 5-1 identifies the facilities and equipment associated with the ONG system segments. Table 5-3 provides examples of the typical facilities and equipment that comprise ONG systems.

Figure 5-1: Segments of Oil and Natural Gas Systems



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

Table 5-3: Emission Sources 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 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

5.1.2.1 Oil and Natural Gas Systems Emission Projections

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for natural gas and oil systems included ONG production, consumption, and refining statistics and forecasts from EIA (2018a; 2018b) and the BP Statistical Review of World Energy (2017). Emissions from natural gas and oil systems were disaggregated into Gas Production and Processing, Gas Transmission, Storage, and Distribution, Oil Production, and Oil Refining. The Tier 1 basic equation to estimate CH₄ emissions from ONG systems is as follows:

$$\text{Total Fugitive CH}_4 \text{ Emissions} = (\text{Annual Oil Production} \times \text{Emission Factors} + \text{Annual Crude Oil Refined} \times \text{Emission Factor}) + (\text{Annual Natural Gas Production} \times \text{Emission Factors} + \text{Annual Natural Gas Consumption} \times \text{Emission Factors})$$

Emissions from ONG systems were disaggregated into the following categories:

- gas production and processing
- gas transmission, storage, and distribution
- oil production
- oil refining

These categories represent a combination of IPCC emission factors for each of the given segments. IPCC factors determine emission estimates based on specific drivers such as total gas or oil production within a country. Because emission factors are held constant, the driver for determining fugitive CH₄ emissions from ONG is the respective production and consumption of these fuels.

Activity Data

Historical

- The EPA obtained historical ONG production and consumption data from EIA (2018a; 2018b) for 1990 through 2015. For refineries, the EPA obtained refinery throughput data from the BP Statistical Review of World Energy (BP, 2017).

Projected

- Projections of ONG production and consumption were available from the EIA *International Energy Outlook* (EIA, 2017). The EPA used growth rates as provided by EIA Reference Case projections for each year from 2014 through 2050. These growth rates were available by country or region. When available by region, the EPA assumed all countries within that region have that region's growth rate.

Emission Factors

Historical and Projected

- The EPA used 2006 IPCC Guidelines default factors for natural gas production (IPCC, 2006) (which includes both natural gas production and processing), natural gas consumption (which includes natural gas transmission, distribution, and storage), oil production, oil refining, and venting and flaring for 1990, 1995, 2000, 2005, and 2010 emissions. When the 2006 IPCC Guidelines provided only ranges for emission factors (as opposed to central estimates), the midpoint of the range was used.
- The EPA multiplied appropriate ONG production, consumption, and refining statistics for 1990, 1995, 2000, 2005, and 2010 by IPCC (IPCC, 2006) default factors.

If emissions were not reported and EIA production data were not available for a country, the EPA assumed zero emissions for this source.

Each emission estimate disaggregation relied on a composite IPCC factor and an applicable activity driver. To illustrate which emission factors were combined and used to drive emissions, Table 5-4 shows the considered factors per IPCC's definition for each disaggregation of results (IPCC, 2006). Emissions were determined using this combination (typically a weighted total) of various segments within the ONG industry. Each segment factor used is representative of the varying pertinent fugitive and venting emission sources per IPCC's methodology. For instance, associated gas emissions were considered in the oil production venting estimate.

Table 5-4: IPCC Emission Factors by Disaggregation

Disaggregation	Relevant IPCC Factor	Activity Driver Used
Gas production and processing	Gas production, fugitives; gas processing, default weighted total fugitives and flaring	Gas production
Gas transmission, storage, and distribution	Gas transmission, fugitives and venting; gas storage, all; gas distribution, all	Gas consumption
Oil production ^a	Oil production, default weighted total fugitives, venting, and flaring; well drilling, testing, and servicing, venting and flaring	Oil production
Oil refining	Oil refining, all	Oil throughput

^aIncludes associated gas emissions.

Table 5-5 shows the aggregate emission factor value used for each of the above emission categories. For clarity, units are given according to IPCC's definition. The factors shown in the table represent A1 (developed) countries, whereas IPCC gives comparable factors with higher estimates for Non-A1 countries. Both country designation emissions were developed using the same combination of representative IPCC factors within each segment as shown in Table 5-4. The highest uncertainties are expected to be related to venting and flaring estimates because present infrastructure and practices can vary significantly by country (Soltanieh, 2016).

Table 5-5: Aggregate IPCC Emission Factor by Driver

Driver	Aggregate A1 IPCC Factor
Gas produced	0.001932 Gg/MMm ³
Gas consumed	0.001580 Gg/MMm ³
Oil produced	0.011115 Gg/km ³
Crude refined	0.000022 Gg/km ³

Because the developed emission factors for gas and oil production are so much higher in magnitude than the gas-consumed and crude-refined factors that use similar drivers, respectively, trends in emissions are implicitly more focused on those drivers. Further, oil production is universally the highest estimated segment using this methodology. For example,

based on the application of this methodology, in 2015, oil production comprised 92% of all emissions in Saudi Arabia with 6% attributed to gas production. In contrast, the IPCC crude-refined factor is so low that emission estimates in this segment have virtually no overall impact on results.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainties

The greatest uncertainties are due to the use of default emission factors and difficulties in projecting ONG consumption and production through 2050 for rapidly changing global economies such as those in the former Soviet Union (FSU) and developing Asia. The emission factors provided in the *2006 IPCC Guidelines* have a wide

range in values, and the midpoint of the range may not be representative of country-level emission estimates. There could be some minor overlap in emissions between the given disaggregation of categories. The factors used were also developed in a year prior to this study and may not exactly represent current conditions in a complex and quickly changing industry. In addition, CH₄ emissions from ONG systems are not linearly related to throughput, so the IPCC Tier 1 methodology and emission factors can lead to overestimates.

While the Tier 1 oil production emission estimates derived from IPCC factors are substantially higher than other segments, this could be due to the nature of how the factors themselves were developed. Suggesting that all emissions in these categories represent each segment exclusively, as stated above, may not be accurate. As defined, oil production contains emission estimates from well testing and drilling because IPCC factors are in terms of total oil production. However, this source may also contain emissions that could be considered gas production. Given this, there is a possibility of overlap between the emission categories.

IPCC also provides multiple oil production emission factors based on varying resource types such as conventional oil, heavy oil/bitumen, and synthetic crude. The factor used for this segment is based on the given default IPCC weighted factor. However, these varying resource types may not be applicable to most countries because conventional oil is the most widely processed resource type. Further, within the conventional oil resource type, the onshore fugitive emission factor for oil production has a large variance. Any choice of IPCC factor to use can have an evident impact on the disaggregation of results.

In addition to the differences in magnitude between segments, emission estimates through this methodology are affected by the range that IPCC publishes for certain factors as mentioned for oil production fugitives above. While certain factors may exhibit one value, others can range, providing a drastically different Tier 1 estimate. These ranges can be associated with various factors such as offshore versus onshore activity or the use of reciprocating versus centrifugal compressors. For instance, in the gas production fugitives factor, onshore emissions represent the higher range value, whereas offshore activities are associated with the lower range.

Given this variation, further disaggregation and improvement could be done given the appropriate data. Data improvements could include onshore and offshore production values for each country with separate Tier 1 estimates for each country in these sectors using the appropriate factor. Further, typical usage of compressor types in certain countries (reciprocating/centrifugal) could illustrate which factor should be used with gas consumption drivers. However, because of the lack of these data, the EPA focused primarily on the average of these ranges to generate results. Given the vast range of global oil and gas industry conditions and the inherent uncertainty included in using a single emission factor for overall segments, the average range of these factors may represent the best available estimate. Further, the EPA also reviewed results using only the high range, low range, and a geometric average when available to investigate the impact that different factors have on overall emission estimates and to consider alternatives.

5.1.2.2 Oil and Natural Gas Systems Mitigation Options Considered

Within the four segments of ONG systems, a number of abatement measures can be applied to mitigate CH₄ 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 are available to mitigate CH₄ 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 directed inspection and maintenance, and installation of new equipment. ONG industry-related voluntary

programs such as the Global Methane Initiative (GMI) and the EPA's Natural Gas STAR Program, which are aimed at identifying cost-effective CH₄ emission reduction opportunities, have developed a well-documented catalog of potential CH₄ abatement measures that are applicable across the segments of the ONG system. Abatement measures documented by the EPA'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 emission rate and the value of energy recovered. This analysis used 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 Table 5-6 provide an overview of the options considered in each segment of the oil and gas sector.

Table 5-6: 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
Gas Production Segment					
Directed inspection & maintenance at gas production facilities	Chemical injection pumps	—	6,675	1	40%
Installing surge vessels for capturing blowdown vents	Compressor blowdowns	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	Nonassociated gas wells	—	817	1	95%

(continued)

Table 5-6: 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
Gas Production Segment (continued)					
Installing plunger lift systems in gas wells	Nonassociated 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 blowdown (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%
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 (liquid petroleum gas wells)	5,646	(13,855)	5	40%

(continued)

Table 5-6: 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
Gas Processing Segment					
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%
Transmission Segment					
Directed inspection & 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%

(continued)

Table 5-6: 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
Transmission Segment (continued)					
Installing catalytic converters on gas fueled engines and turbines	Engine/turbine exhaust vented	7,924	4,374	10	56%
Directed inspection & maintenance at gate stations and surface facilities	M&R (Trans. Co. Interconnect)	—	1,741	1	72%
Directed inspection & 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 & 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 & maintenance at compressor stations	Stations	—	1,398	1	85%
Directed inspection & maintenance at gas storage wells	Wells (storage)	—	651	1	95%
Distribution Segment					
Directed inspection & 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%

(continued)

Table 5-6: 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
Distribution Segment (continued)					
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.

^b Lower technical effectiveness is due to limited applicability at liquid petroleum gas wells.

5.1.2.3 Technical and Economic Characteristics Summary

The MAC analysis approach consisted 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 nonenergy inputs. Step 4 was to compute the break-even prices for each country-specific abatement measure.

Defining International Model Facilities for the Analysis

For this analysis, we developed model ONG systems for each segment based initially on the EPA ONG system emission inventory. Scaling factors were developed based on country-specific activity factors developed from the international statistics illustrated in **Error! Reference source not found.**. Where reliable data were available, we made international adjustments to reflect specific country systems. For countries for which data were not available, this analysis assumed the oil and gas system was similar to that in the United States in terms of the distribution of emissions (total BAU emissions for each country are exogenous to the MAC model obtained from EPA [2012a]). The relative international factor was multiplied by the percentage share of U.S. oil and gas CH₄ emission inventory at the segment/component source level (e.g., compressors, valves, connections, pneumatic devices). The resulting Technical Applicability factor was 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 technical applicability factor by the baseline emissions yields the subset of emissions available for reductions from each component source and abatement measure. The technical applicability factor comprises two parts. The U.S. 2010 GHG emission inventory serves as the basis for the distribution of emissions across the constituent components (see EPA, 2012b, Annex 3). The second component of the technical applicability factor is the country- and segment-specific relative activity factor (e.g., total oil production, gross natural gas production).

Estimating Abatement Project Costs and Benefits

The analysis begins with technology costs for the United States as reported in the EPA Lessons Learned documentation. We applied the Nelson-Farrar¹⁵ 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 5-7 presents the break-even prices for selected ONG system abatement measures for the United States in 2010. Break-even prices for other countries differ based on differences in ONG operational spatial distribution and production technologies, reservoir types, and differences in input prices for mitigation technologies. For this analysis, we used the abatement measure costs, revenue, and reduction efficiency as described in the previous section to estimate the break-even price for each abatement measure.

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 served as the denominator in the break-even price calculation.

In Table 5-7, we present abatement cost and revenues per metric ton of CO₂ equivalent (tCO₂e) reduced for the abatement measures with the largest national emission 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 5-7 were calculated by subtracting the annual revenues from the annualized costs.

5.1.2.4 Sector-Level Trends/Considerations

The objective in assessing the sectoral trends is to understand how emissions differ across countries and how they vary over time. Assessing trends 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 oil and gas 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. **Error! Reference source not found.** presents these key statistics for the 10 largest emitting countries in 2010.

¹⁵ Nelson-Farrar Annual Cost Indices are available in the first issue of each quarter of the *Oil and Gas Journal*.

Table 5-7: Example Break-Even Price Calculation based on 2010 MAC for the United States

Abatement Measure	System Component/ Process	Reduced Emissions per Unit (tCO ₂ e)	Annualized Capital Costs (\$/tCO ₂ e)	Annual Cost (\$/tCO ₂ e)	Annual Revenue (\$/tCO ₂ e)	Tax Benefit of Depreciation (\$/tCO ₂ e)	Break-even Price (\$/tCO ₂ e)	National Incremental Reductions (MtCO ₂ e)
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 & 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	Reciprocating compressor	1,014.8	\$1.07	\$0.00	\$10.01	\$0.32	-\$9.26	5.65
Distribution								
Directed inspection & 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 & 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 assumed a 10% discount rate and a 40% tax rate. Annual energy benefits were based on a natural gas price of \$4/Mcf.

Table 5-8: International Statistics on Key Activity Drivers: 2010

Country	2010 Emissions (MtCO ₂ e)	Dry Natural Gas Production ^a (Bcf/year)	Crude Oil Production ^b (Mbbl/day)	Gas Processing Plant Throughput ^c (MMcf/d)	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. 2018a. International Energy Statistics: Gross Natural Gas Production.^b EIA. 2018b. 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. <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., 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.

Table 5-9 shows the allocation of baseline emissions to the five segments of the ONG system. These percentages determine the distribution of emissions over the production supply chain.

Table 5-9: Allocation of Baseline Emissions to the Five Segments of the ONG System

Regions	OIL	GAS_PRODUCTION	GAS_PROCESSING	GAS_TRANSMISSION	GAS_DIST
Africa	0%	69%	10%	17%	3%
Asia	1%	42%	35%	14%	8%
Central and South America	1%	56%	10%	25%	8%
Eurasia	0%	40%	0%	47%	13%
Europe	2%	43%	0%	33%	21%
Middle East	1%	63%	8%	21%	7%
North America	5%	60%	9%	17%	8%

5.1.2.5 References

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5.1.3 Stationary and Mobile Combustion

Stationary and mobile combustion consists of CH₄ and N₂O emissions from the combustion of fossil fuels in vehicles; power plants; and residential, commercial, and industrial stationary sources.

5.1.3.1 Stationary and Mobile Combustion Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for stationary and mobile combustion included coal, oil and gas consumption from EIA (2018) and projected fuel consumption data from EIA (2017). The Tier 1 basic equation to estimate CH₄ and N₂O emissions from stationary and mobile combustion is as follows:

$$CH_4 \text{ Emissions} = \text{Annual Fuel Consumption (by fuel type)} \times \text{Emission Factor (by fuel type)} \quad (5.1)$$

$$N_2O \text{ Emissions} = \text{Annual Fuel Consumption (by fuel type)} \times \text{Emission Factor (by fuel type)} \quad (5.2)$$

The driving factors for determining emissions from stationary and mobile combustion are activity data (fuel consumption) and activity data growth rates.

Activity Data

Historical

- Fuel consumption data by fuel type (coal, oil, and gas) were obtained from EIA's International Energy Statistics Database (EIA, 2018). While the database contained full time-series data in mass units for 1990 through 2014, data in energy units were accurate only for 2010 through 2014. Thus, the trend from the mass data was used to back cast the energy data for 1990 through 2010.

Projected

- Projected fuel consumption data by fuel type (coal, oil, and gas) were obtained from EIA's *International Energy Outlook* database (EIA, 2017). The data were then converted to annual growth rates, which were used to project the historical data. The data were provided through 2040, so the 2040 growth rate was assumed to be constant from 2041 through 2050. Projected fuel consumption data were available at the country level for some developed countries; for all other countries, a regional growth rate was applied.

Emission Factors

Historical and Projected

- Tier 1 emission factors were obtained from IPCC's *2006 IPCC Guidelines*. Because the activity data are broken out by fuel type and the IPCC emission factors are broken out by IPCC sector, the emission factor for each fuel type was mapped to its closest matching IPCC sector (e.g., the emission factor for jet fuel was mapped to the IPCC's Aviation sector). The same emission factors were applied for each country.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

Uncertainties in the emission estimates include differences between regional- and country-level growth rates, assumptions that activity data growth rates from 2041 through 2050 will equal that of 2040, and the IPCC Tier 1 default emission factors. For stationary combustion sources, this high degree of uncertainty is a result of the lack of relevant measurements, uncertainties in measurements, or an insufficient understanding of the emission generating process (IPCC, 2006). The *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (IPCC, 2000) estimates uncertainty for the stationary CH₄ combustion emission factors at ±50 to 150%. Stationary combustion N₂O combustion emission factors are highly uncertain due to limited testing data on which the factors are based. In addition, the use of uncontrolled stationary IPCC default emission factors may overestimate emissions in those developing countries that have adopted some level of emission control strategies for combustion sources.

Uncertainty in N₂O and CH₄ emission factors for mobile combustion depends on a number of factors, including uncertainties in fuel composition, fleet age distribution and other vehicle characteristics, and maintenance patterns of the vehicle stock, to name a few (IPCC, 2000).

5.1.3.2 Stationary and Mobile Combustion Mitigation Methodology

The EPA has not estimated mitigation potential from stationary and mobile combustion because of the lack of available data on mitigation options.

5.1.3.3 References

Intergovernmental Panel on Climate Change. 2000. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC-XVI/Doc.10 (1.IV.2000). Montreal, Canada: Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

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U.S. Energy Information Administration. 2018. International Energy Statistics Portal. Washington, DC: Energy Information Administration, U.S. Department of Energy. Online Database. Available online at www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

5.1.4 Biomass Combustion

Biomass combustion consists of CH₄ and N₂O emissions from the incomplete combustion of biofuels, wood, and charcoal.

5.1.4.1 Biomass Combustion Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3 Generating the Composite Emission Projections, for additional information). Activity data for biomass combustion included biofuel consumption from EIA (2018) with growth rates from EIA (2017) and charcoal and wood fuel consumption from FAO (2016) with growth rates from FAO (2010). Emissions from the biomass combustion source category were disaggregated according to emissions from biofuel consumption and emissions from wood fuel and charcoal consumption.

The Tier 1 basic equation to estimate CH₄ and N₂O emissions from biomass combustion is as follows:

$$CH_4 \text{ Emissions} = \text{Fuel Consumption (by fuel type)} \times CH_4 \text{ Emission Factor (by fuel type)} \quad (5.3)$$

$$N_2O \text{ Emissions} = \text{Fuel Consumption (by fuel type)} \times N_2O \text{ Emission Factor (by fuel type)} \quad (5.4)$$

Biofuel (in barrels), charcoal (in metric tons), and wood fuel (in cubic meters) were converted to energy units using energy conversion values before multiplying each by its fuel-specific emission factor. The driving factors for determining emissions were both historical activity data and projected growth rates.

Activity Data

Historical

- Charcoal and wood fuel activity data were obtained from the FAO's FAOSTAT database (FAO, 2016).
- Biofuel activity data were obtained from EIA's International Energy Statistics database (EIA, 2018).

Projected

- Growth rates for wood fuel consumption, broken out by region, were obtained from FAO (2010). Growth rates of charcoal consumption were assumed to equal that of wood fuel. Because growth rates are not provided after 2030, the growth rate for 2031 through 2050 was assumed to equal that of 2021 through 2030.
- Growth rates for biofuels consumption, broken out by region, were obtained from EIA's *International Energy Outlook* (EIA, 2017).
- Because of the absence of country-specific growth rate information, individual countries were mapped to each region to obtain country-level growth rates.

Emission Factors

Historical and Projected

- Tier 1 emission factors were obtained from IPCC (2006). For charcoal and biofuels, the exact IPCC values were used for all countries. For wood fuel, an energy-weighted emission factor was calculated. Because the IPCC emission factors are different in each sector and the wood fuel data from FAOSTAT were not broken out by sector, an energy-weighted factor was calculated to reflect the previous EPA-published

report (EPA, 2012) in the Energy, Industrial, Transport, and Other sectors. Given that most wood fuel burning occurs in the Other sector (i.e., the residential and commercial sectors) based on the previous EPA-published report (EPA, 2012), the emission factor is heavily weighted (80%) to the IPCC's Other emission factor.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainties

Uncertainties in the emission estimates occur because emission factors for biomass combustion are not as well developed as those for fossil fuels because of limited test data for the variety of types and conditions under which these fuels are burned. Uncertainties are at least as great as those for fossil fuel CH₄ and N₂O factors (\pm 50 to 150%). Activity data for biomass fuel combustion also tend to be much more uncertain than fossil fuels because of the smaller, dispersed, and localized collection and use of these fuels, which makes tracking consumption more difficult. Detailed data related to the location and magnitude of biomass combustion are limited.

Furthermore, energy values used to convert mass and volume of biomass sources into energy units contain significant uncertainty.

Uncertainty also occurs due to the lack of sectoral granularity in the wood fuel activity data. The emission factor for energy and industry for CH₄ is an order of magnitude smaller than that of the residential and commercial sectors.

5.1.4.2 Biomass Combustion Mitigation Methodology

The EPA has not estimated the mitigation potential from biomass combustion because of the lack of available data on mitigation options.

5.1.4.3 References

Food and Agriculture Organization of the United Nations. 2010. *Future Trends in Energy, Climate and Woodfuel Use*. Rome, Italy: Food and Agriculture Organization of the United Nations. Available online at <http://www.fao.org/docrep/013/i1756e/i1756e05.pdf>

Food and Agriculture Organization of the United Nations. 2016. *Forestry Production and Trade*. Rome, Italy: Food and Agriculture Organization of the United Nations. Online Databased Accessed: August 2016. Available online at <http://www.fao.org/faostat/en/#data/FO>

Intergovernmental Panel on Climate Change. 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.

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U.S. Environmental Protection Agency. 2012. *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990-2030*. Available online at https://www.epa.gov/sites/production/files/2016-08/documents/epa_global_nonco2_projections_dec2012.pdf

5.1.5 Other Energy

This source category includes solid fuel transformation and waste incineration.

5.1.5.1 Other Energy Projections Methodology

This source category solely comprises countries that report data to the UNFCCC database. The EPA did not perform Tier 1 calculations for other energy sources. The EPA obtained historical values for 1990 through 2012 and held 2015 through 2050 values constant at 2012 levels for each country.

5.1.5.2 Other Energy Mitigation Methodology

The EPA has not estimated mitigation potential from other energy because of the lack of available data on mitigation options.

5.2 Industrial Processes

This section presents the methodologies used to develop global non-CO₂ emission projections and mitigation estimates from the industrial processes sector. The industrial processes sector includes industrial sources of N₂O and CH₄, along with several sources of high-GWP gases. The high-GWP sources include the use of substitutes for ODSs and industrial sources of HFCs, PFCs, and SF₆. The categories and their GHG emission and mitigation estimates presented in this section are as follows:

- adipic acid and nitric acid production (N₂O)
- use of substitutes for ozone-depleting substances (HFCs, PFCs)
- hydrochlorofluorocarbons (HCFCs)-22 production (HFCs)
- operation of electric power systems (SF₆)
- primary aluminum production (PFCs)
- semiconductor manufacturing (HFCs, PFCs, SF₆)
- magnesium manufacturing (SF₆)
- flat panel display manufacturing (PFCs, SF₆)
- photovoltaic manufacturing (PFCs)
- other industrial processes sources (CH₄, N₂O) (projections only), including:
 - chemical production (CH₄)
 - iron and steel production (CH₄)
 - metal production (CH₄, N₂O)
 - mineral products (CH₄)
 - petrochemical Production (CH₄)
 - silicon carbide production (CH₄)
 - solvent and other product use (N₂O)

5.2.1 Nitric and Adipic Acid Production

The nitric and adipic acid production source category consists of N₂O emissions from the production of adipic acid and nitric acid. Nitric acid (HNO₃) is an inorganic compound used primarily to make synthetic commercial fertilizer. The production of nitric and adipic acid results in significant N₂O emissions as a by-product. Adipic acid (hexane-1, 6-dioic acid) is a white crystalline solid used as a feedstock in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants.

5.2.1.1 Nitric and Adipic Acid Production Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for adipic acid and nitric acid production included adipic acid production capacity from Chemical Week (2007) and ICIS Europe (2011, 2013, and 2015) and production utilization from SRI (2010) and Chemical Week (1999 and 2007); adipic acid consumption growth rate from SRI (2010); nitrogenous fertilizer production from International Fertilizer Industry Association(IFAI) (2016); and projections of fertilizer consumption from Tenkorang and Lowenberg-DeBoer (2008). Emissions from the nitric and adipic acid production emission source category were disaggregated to nitric acid production and adipic acid production source categories. Emission reductions from currently-installed bio-based adipic acid production

capacity were included in the emission estimates, while no abatement technology was assumed to be already installed for nitric acid production capacity.

The Tier 1 base case equations to estimate N₂O emissions from adipic acid and nitric acid production are as follows:

$$N_2O \text{ emissions} = \text{Adipic Acid Production} * \text{Partially Abated Emission Factor} \quad (5.5)$$

$$N_2O \text{ emissions} = \text{Nitric Acid Production} * \text{Unabated Emission Factor} \quad (5.6)$$

For adipic acid production, the driving factor for determining projected emissions is the projected 3.5% annual growth rate in global production capacity, although the assumed increasing adoption of bio-based adipic acid production technologies that do not emit N₂O mitigates the projected emissions increase to some extent. For nitric acid production, the driving factor for determining projected emissions is projected increases in nitrogenous fertilizer production, which is used to approximate production of the compound.

Activity Data

Historical

Adipic Acid

- When country-reported emission data were unavailable, production data were estimated based on adipic acid plant production capacity figures and estimated capacity utilization. Capacity utilization was assumed to be 75% in 1990, 80% in 1995, 90% in 2000 and 2005, and 88% in 2010 through 2050 (SRI, 2010; Chemical Week, 2007, 1999). Adipic acid production data at the country level were obtained for 1990, 1995, 1998, 2007, 2009, 2011, 2013, and 2015 (Chemical Week, 2007; ICIS Europe, 2011, 2013, 2015)

Nitric Acid

- When country-reported emission data were unavailable, country-specific fertilizer production data were used (International Fertilizer Industry Association [IFA], 2016).

Projected

Adipic Acid

- Global adipic acid consumption was forecasted to increase by 3.5% annually for the period 2008 through 2013 (SRI, 2010). In this analysis, projections of global adipic acid consumption were used as a surrogate for production projections, and the 3.5% growth rate was applied from 2015 through 2050. Known bio-based adipic acid capacity was assumed through 2007, after which bio-based capacity was maintained constant.

Nitric Acid

- The growth rates of fertilizer consumption from 2015 through 2030 were estimated by using the regional N fertilizer consumption projections available from Tenkorang and Lowenberg-DeBoer et al. (2008). Tenkorang and Lowenberg-DeBoer et al. (2008) provided regional fertilizer use for 2015 and 2030. Fertilizer use for 2020 and 2025 were interpolated. These consumption projections were then used to calculate average annual growth rates for the 5-year increments between 2015 and 2030, which in turn were used to project fertilizer use by country.
- The average annual percentage change in fertilizer use by region for the remainder of the projected time series (i.e., 2030 through 2050), was available from FAO (2012). The average annual regional growth rates for the 5-year increments between 2030 and 2050 were used to project fertilizer use by country. Countries were assigned to regions based on Annex I of Tenkorang and Lowenberg-DeBoer (2008) and Appendix 1 of FAO (2012).

Emission Factors

Historical and Projected

Adipic Acid

- The IPCC uncontrolled default emission factor for N₂O emissions is 300 kilograms N₂O per metric ton adipic acid (IPCC, 2006). The N₂O emission factor is partially abated because the emission factor for bio-based production was assumed to equal zero based on review of the bio-based technologies. Using known installations through 2007, bio-based adipic acid capacity increases from 0% of installed capacity in 2002 to a peak of 28% in 2011 and declines to 7% in 2050 because of an assumed constant amount of bio-based adipic acid production capacity and increasing unabated adipic acid production. The emission factor for conventional adipic acid production was assumed to be the same across all countries.

Nitric Acid

- The unabated emission factor used for Tier 1 calculations is 9 kilograms N₂O per metric ton nitric acid (IPCC, 2006). The unabated emission factor was assumed to be the same across all countries.

Emission Reductions in Baseline Scenario

Adipic Acid

- Emission reductions from currently installed bio-based adipic acid production capacity were included in the base case Tier 1 estimates, based on a market assessment from Shen et al. (2009).

Nitric Acid

- While no emission reductions were included in the base case Tier 1 estimates for nitric acid production, historical emission reductions from N₂O abatement technology are included in this analysis to the extent that abatement is reflected in country-reported emission estimates.

Uncertainties

In general, the IPCC default adipic acid emission factor is more certain than the IPCC default nitric acid emission factor because the adipic acid emission factor is derived from stoichiometry of the process chemical reaction. The *2006 IPCC Guidelines* (IPCC, 2006) estimate an uncertainty range for the unabated adipic acid emission factor of ±10%. The uncertainty range given for the unabated nitric acid emission factor is ±40%. A more thorough understanding of country-specific production processes and control technologies would reduce uncertainty in these estimates by allowing the use of more specific emission factors. Proxying projected nitric acid production to projected nitrogen fertilizer demand growth is a source of uncertainty because many countries that use nitrogenous fertilizer do not produce it. Other sources of uncertainty include assumptions in the projected growth rate of global adipic acid production and assumptions of currently installed and projected bio-based adipic acid production.

5.2.1.2 Nitric and Adipic Acid Production Mitigation Options Considered

This analysis considered four abatement measures applied to the chemical processes used to produce nitric and adipic acid to reduce the quantity of N₂O emissions released during the production process. Thermal destruction is the abatement measure applied to the adipic acid production process. The three remaining measures are applicable to the nitric acid production process.

Nitric acid facilities have the option of using specially designed catalysts to control N₂O 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 N₂O. Secondary abatement measures such as homogeneous thermal decomposition and catalytic decomposition are installed at an intermediate point in the production process, removing the N₂O formed through ammonia oxidation. Tertiary

abatement measures, such as catalytic decomposition and nonselective catalytic reduction (NSCR) units are applied to the tail gas streams at the end of the nitric acid 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 break-even prices. Table 5-10 summarizes 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 activities.

Table 5-10: Abatement Measures for Nitric and Adipic Acid Production

Abatement Option	2010 USD				Annual Benefits		Average Reductions (tCO ₂ e/yr)
	Total Installed Capital Cost	Annual O&M Cost	Time Horizon (years)	Technical Efficiency, %	Energy	Non-energy	
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 NSCR 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 tHNO₃/day.

Adipic Acid—N₂O Abatement Methods

Adipic acid facilities typically direct the flue gas to a reductive furnace in a thermal destruction process to reduce nitric oxide (NOx) emissions. Thermal destruction is the combustion of off-gases (including N₂O) in the presence of CH₄. The combustion process converts N₂O to nitrogen, resulting primarily in emissions of NO and some residual N₂O (Ecofys, Fraunhofer ISIR, and Öko-Institute, 2009). Facilities may also employ a catalytic decomposition method to abate the N₂O generated. The EU Emissions Trading System [ETS] and CDM methodologies for this abatement measure suggest that heat generated from the decomposition of N₂O can be used to produce process steam for use in local processes, substituting for more expensive steam generated using fossil fuel alone.

- **Applicability:** This option applies to adipic acid production facilities that do not currently control N₂O emissions. Based on a recent analysis (Schneider et al., 2010), only 9 of the 23 operational facilities in 2010 had unabated N₂O emissions.
- **Technical Effectiveness:** This analysis assumed a 95% efficiency converting N₂O into nitrogen and water.

- **Technical Lifetime:** 20 years
- **Capital Cost:** The initial capital cost is \$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 N₂O 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.

Nitric Acid—Primary Abatement Measures

This group of abatement measures can be applied at the ammonia oxidation stage of the nitric acid production process. Pérez-Ramirez et al. (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 N₂O in the ammonia burner and would require making adjustments to the ammonia oxidation process and/or catalyst (Pérez-Ramirez et al., 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.

Nitric Acid—Secondary Abatement Measures

Secondary abatement measures remove N₂O immediately following the ammonia oxidation stage between the ammonia converter and the absorption column (Pérez-Ramirez et al., 2003). Abatement measures include thermal decomposition and 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 (Pérez-Ramirez et al., 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.

- **Applicability:** This option is applicable to all existing nitric acid plants.
- **Technical Effectiveness:** This analysis assumed an 80% efficiency converting N₂O into nitrogen and water.
- **Technical Lifetime:** 20 years
- **Capital Cost:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumed a capital cost of \$3.5/tonne of HNO₃ production capacity¹⁶ and a plant capacity of 1,000 tHNO₃/day. Using these assumptions, the initial capital costs would equal \$1.3 million (2010 USD).

¹⁶ Based on costs of € 0.25/tHNO₃ reported in 2008 euros (EC, 2008) scaled to 2010 USD using the CEPI and an exchange rate of 1.32 (USD/EUR).

- **Annual O&M Costs:** Annual O&M costs include catalyst replacement and recycling of spent catalyst, replacement of spare catalyst, and loss of production due to catalyst disruptions. This analysis assumed an annual cost of \$1.3/tHNO₃ produced and a plant utilization rate of 90% (Pérez-Ramirez et al., 2003). Following the plant example of a 1,000 tHNO₃/day, the annual cost would be \$0.4 million (2010 USD).
- **Annual Benefits:** No benefits are associated with this option.

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 N₂O (Pérez-Ramirez et al., 2003). Similar to earlier abatement measures, this measure reduces the N₂O into nitrogen and oxygen through thermal or catalytic decomposition.

- **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 assumed a 82% efficiency converting N₂O into nitrogen and water.
- **Technical Lifetime:** 20 years
- **Capital Cost:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumed a capital cost of \$6.3/tonne of HNO₃ production capacity¹⁷ and a plant capacity of 1,000 tHNO₃/day. Using these assumptions, the initial capital costs would equal \$2.3 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 or the lowering of the process pressure. This analysis assumed an annual cost of \$0.6/tHNO₃ produced and a plant utilization rate of 90% (Pérez-Ramirez et al., 2003). Following the plant example of a 1,000 tHNO₃/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.

Nitric Acid—Tertiary Abatement Measure: 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 N₂O 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.

- **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 assumed 90% efficiency converting N₂O into nitrogen and water.

¹⁷ Based on costs of € 0.5/ tHNO₃ 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).

- **Technical Lifetime:** 20 years
- **Capital Cost:** Capital costs include the purchase and installation of the NSCR unit and catalyst. This analysis assumed a capital cost of \$12.6/tonne of HNO₃ production capacity based on \$8.2/tHNO₃ reported in 1991 USD (EPA, 1991) scaled to 2010 USD using the CEPI. Assuming a plant capacity of 1,000 tHNO₃/day, the initial capital cost would equal \$4.6 million (2010 USD).
- **Annual O&M Costs:** Annual costs total \$8.8/tHNO₃ produced. Annual costs include the cost of reagent fuel, labor, maintenance, and other fixed costs for capital recovery and insurance. The 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.

5.2.1.3 Model Facilities

The MAC analysis is based on project costs developed for a set of model facilities based on the abatement measure costs discussed earlier in this section. 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 N₂O emission projections (given) and allocates emissions based on the 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.¹⁸

Adipic Acid—Facility Inventory

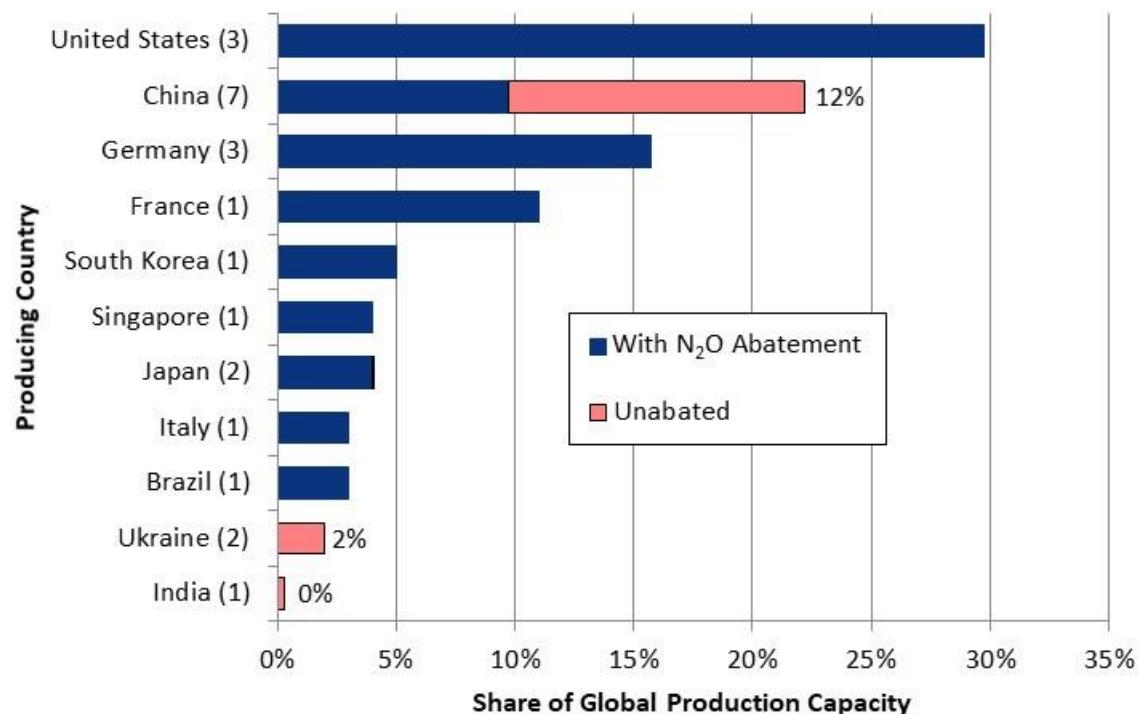
The first step in the analysis was to determine the allocation of projected emissions to nitric and adipic acid production by country. For example, in the United States, adipic acid production accounted for approximately 15% of total baseline emissions in 2010, while the majority of emissions were attributed 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.¹⁹ Schneider and co-authors also identified the N₂O abatement technologies and plant utilization factors. Figure 5-2 summarizes the

¹⁸ Although a number of different processes are 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 2 and 3 of the production process and, therefore, operate at high pressures.

¹⁹ Major changes to previously reported adipic acid inventories (Mainhardt and Kruger, 2000; OECD, 2004) includes the opening of five new plants in China between 2008 and 2009 and the closure of two plants located in Canada and the U.K. In addition, a fourth plant located in the United States was idle between 2008 and 2009 and assumed to continue to idle in 2010 (EPA, 2012).

Figure 5-2: Operational Adipic Acid Production Facilities in 2010 by Share of Global Capacity



Source: Adapted from Schneider, L., M. Lazarus, and A. Kollmuss. 2010. Industrial N₂O Projects Under the CDM: Adipic Acid—A Case of Carbon Leakage? Working Paper No. WP-US-1006. Somerville, MA: Stockholm Environment Institute (SEI). http://ec.europa.eu/clima/consultations/0004/unregistered/cdm_watch_2_en.pdf.

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

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 N₂O emission from adipic acid production by country.

Although 11 countries currently produce adipic acid, only 4 countries (China, Ukraine, Japan, and India) have operational facilities that are known to have no N₂O emission controls in place. As the figure shows, all but 15% of the adipic acid capacity has N₂O abatement controls in place. The 15% of capacity with no N₂O 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 N₂O abatement measures (Schneider et al., 2010; Ecofys et al., 2009; EPA, 2012). In 2005, with the establishment of the CDM methodology for crediting N₂O abatement projects at adipic acid plants, producers in developing countries began to adopt N₂O abatement measures. Schneider and coauthors point out that although the CDM methodology was effective in achieving N₂O reductions in developing countries, it was limited to facilities that were in operation before 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., 2010). China alone was expected to see its capacity more than double in the near term with the opening of five new adipic acid plants between 2011 and 2013 (Zhao, 2011). At the end of

2015, China had seen significant growth in adipic acid capacity, expanding from 320 kt in 2010 to approximately 1,800 kt (CCFGroup, 2016).

Only 15% of global capacity continues to operate with no known N₂O abatement. China and Ukraine account for over 95% of the capacity with unabated N₂O 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 assumed that future abatement potential is limited to the nine plants identified as having no known N₂O abatement measure in place.

Although no information was available on specific plant utilization rates, we assumed utilization rates of 60% for all non-CDM facilities, 85% for CDM facilities,²⁰ 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 estimated net emissions for each country by applying the IPCC emission factor of 300 kg N₂O 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 N₂O (32.2 MtCO₂e) in 2010.

We assumed the net emissions calculated for each country represent adipic acid's representative share of total projected baseline emissions. Table 5-11 provides the percentages used to break out the N₂O emission baseline to adipic acid.

The analysis assumed that N₂O emissions from adipic acid production account for the percentage of total sectoral baseline listed in Table 5-11. We attribute the balance of baseline emissions to nitric acid production.

Table 5-11: Adipic Acid–Producing Countries' Share of Baseline Emissions^a

Country	Share of N ₂ O Baseline, %	
	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

^aFor 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 in EPA (2013) (36%).

^bChina, Japan, and Ukraine percentages used are from the EMF 21 MAC model (EPA, 2006).

²⁰ Facilities located in Brazil, China, and South Korea.

Nitric Acid Model Facility Description

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 organized the model facilities based on production capacity. All four facility types were assumed to have an uncontrolled emission factor of 8.5 kg N₂O per tHNO₃ produced²¹ (IPCC, 2006). Table 5-12 summarizes the model facilities for nitric acid production by capacity and resulting annual N₂O emissions.

Table 5-12: Model Nitric Acid Facilities Assumptions

Model Plants	Production (tHNO ₃ /yr)	Annual N ₂ O Emissions (uncontrolled) (tN ₂ O)
Small	30,600	261
Medium	113,333	968
Large	226,667	1,936
Modern plant	340,000	2,904

5.2.1.4 Sector-Level Trends and Considerations

The following additional data and detail would improve our abatement potential estimates:

- Abatement technology utilization rates: Active CDM and Joint Implementation abatement projects in this sector have reported N₂O reduction efficiencies and utilization rates significantly higher than the default assumptions provided by the IPCC.
- Technology applicability: Across various nitric acid production processes having a better understanding of how costs for abatement measures would vary with each process.

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²¹ The default emissions factor for the high-pressure process is 9 kg N₂O per ton of nitric acid; the default emissions factor for the medium-pressure processes is 7 kg N₂O per ton of nitric acid produced.

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5.2.2 F-GHG Emissions from Semiconductor Manufacturing

Semiconductor manufacturing consists of HFC, PFC, SF₆, and NF₃ emissions from two repeated activities: (1) cleaning tool chambers used to deposit thin films on substrate surfaces, a process referred to as chemical vapor deposition (CVD) chamber cleaning, and (2) etching intricate patterns into successive layers of films and metals, a process referred to as plasma etching. Film deposition and etching processes begin with the semiconductive crystalline silicon (Si) wafer (or another substrate) and are completed once successive films (layers) are deposited and etched to form a device. EPA GHGRP data indicate that approximately 27% to 46% of emissions result from chamber cleaning processes and 54% to 73% from etching processes (EPA, 2014, 2015, 2016).

5.2.2.1 Semiconductor Manufacturing Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3 Generating the Composite Emission Projections, for additional information). Activity data for semiconductor manufacturing included annual semiconductor manufacturing capacity by country from World Fab Watch (SEMI 1996, 2001, 2002, 2003, 2006 and 2007) and World Fab Forecast (SEMI 2008, 2009, 2010, 2011, 2012, and 2016), and growth of manufacturing capacities based on the growth in each country's gross domestic product. Emission factors were based on EPA's GHGRP data and activity from the aforementioned sources (2016). Emission reductions were incorporated based on the EPA and U.S. semiconductor industry's voluntary partnership and the global industry commitment through the World Semiconductor Council to reduce F-GHG emissions.

The Tier 1 equation to estimate HFC, PFC, SF₆, and NF₃ emissions from semiconductor manufacturing is as follows:

$$E_i = EF_i * C_U * C_d * [1 - (a_i * d_i)] \quad (5.7)$$

where:

E_i	=	Emissions of gas i
EF_i	=	IPCC Tier 1 emission factor for gas i
C_u	=	Annual plant production capacity utilization
C_d	=	Manufacturing design capacity
a_i	=	Abatement fraction of gas i
d_i	=	Destruction or removal efficiency of gas i

Emissions vary over time as a function of all the variables above: the emission factor is driven by advancements in manufacturing technology, the capacity utilization and capacity design are driven by the demand of the semiconductor products, the abatement fraction is facility specific and depends on whether the manufacturing facility uses abatement devices, and the destruction or removal efficiency depends on the type of abatement technology used.

Activity Data

Historical

Historical activity data consisted of the annual semiconductor manufacturing capacity by country, broken out by 200-mm and 300-mm wafer size.²² These data are provided by the World Fab Watch (SEMI, July 1996, 2001, 2002, April 2003, 2006 and 2007 editions) and World Fab Forecast (SEMI, 2008, 2009, 2010, 2011, 2012, and 2016 editions).²³ These sources were used to develop country-specific capacity shares for 1995, 2000, 2005, 2010, and 2015.²⁴ Beginning in 2006, World Fab Forecast provided activity data separated out by 200-mm and 300-mm wafer sizes. However, for the years 1990 through 2005 when World Fab Watch was used, manufacturing capacities were not distinguished by wafer size in the data source. Therefore, it was assumed that all global capacity before 2006 was for the 200-mm wafer size.

Projected

For all countries, their manufacturing capacities from 2020 through 2050 were estimated by growing the manufacturing capacity at a rate equivalent to the growth in each country's GDP over the same time period. These total capacities were then disaggregated by 200-mm and 300-mm wafer sizes based on projected shares of each wafer size. The projected shares of capacity for 200-mm wafers were developed through linear extrapolation of historical data from 2006 through 2017. The shares of 300-mm wafer capacity were calculated as (1–200-mm share). This projection by 200-mm and 300-mm shares was done to ensure that the recent increase in shares of 300-mm fabs compared against 200-mm fabs (growing from only 42% of global production capacity in 2006 to 51% in 2017) was represented for the projected years. In addition, if a particular country had no 300-mm wafer sizes in the reported historical data, then that country was assumed to continue using only 200-mm fabs in the projections through 2050.

Emission Factors

Historical and Projected

Emissions were estimated using EPA-derived emission factors for F-GHG emissions in the units of kgCO₂e/cm². Emission factors were developed using EPA GHGRP-reported data (EPA, 2017) and activity data as described above. Emission factors were obtained for each 200-mm and 300-mm wafer size using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of F-GHGs were regressed on the corresponding manufacturing capacity (m²) to estimate an aggregate F-GHG emission factor (CO₂ Eq/m²). The slope of the RTO model is the emission factor of the subpopulation.

The EPA developed 2011 F-GHG emission factors (subject to the availability of both the GHGRP data and World Fab Forecast data) and applied them to both the historical and projected data. The emission factors used are presented in Table 5-13.

Table 5-13: Emission Factor Used for Semiconductor Manufacturing

Wafer Size	Emission Factor kg CO ₂ e/cm ²	
	Historical	Projected
200 mm	1.06	0.89
300 mm	0.43	0.36

²² All wafer sizes less than 200 mm were included in the 200-mm category, and all wafer sizes greater than 300 mm were included in the 300-mm category.

²³ The World Fab Watch was the predecessor of the World Fab Forecast.

²⁴ Country-specific capacity shares in 1990 were assumed to be equivalent to those in 1995.

When comparing country emissions as calculated using the approach described above (Tier 1) with emissions reported to the UNFCCC, cases of over- or underestimations were identified. To address these instances, when feasible, country emission projections were estimated using the most recent country-reported data (2015) and the growth rates and country shares described above.

Finally, shares of emissions by gas were calculated from the historical reported emissions to give percentages of HFC, PFC, SF₆, and NF₃ emissions of total semiconductor emissions. These shares were applied to country emissions for all years, holding 2015 shares constant for all future years, to determine country emissions by type of gas. The assumption to hold 2015 shares constant in the projections was made because it cannot be known at this time what new processes and technologies will be used in semiconductor manufacturing, which is a high-tech and rapidly evolving industry. As a result, if new technologies come online in future years, the shares of emissions could change.

Emission Reductions in Baseline Scenario

In the 1990s, the absence of emission control measures, rapid growth of the semiconductor industry (11 to 12% per year through the late 1990s), and increasing complexity of microchips could have potentially resulted in significantly increased future emissions from semiconductor manufacturing. In response, the EPA and the U.S. semiconductor industry launched a voluntary partnership to reduce F-GHG emissions in 1996. In 1999, the U.S. partnership catalyzed a global industry commitment through the World Semiconductor Council (WSC). Most WSC member countries—the United States, EU, Japan, South Korea, and Taiwan²⁵—voluntarily committed to reduce HFC, PFC, SF₆, and NF₃ emissions to 90% of 1995 levels by 2010.²⁶ At the end of the 2010 WSC goal, the member countries reduced absolute emissions by 32% below the baseline to a level of 2.7 MMTCE, surpassing the 10% reduction target (WSC, 2016). WSC set a subsequent goal for 2020 to implement best practices for new semiconductor fabs to result in a normalized emission rate (NER) of 0.22 kgCO₂e/cm², which is equivalent to a 30% NER reduction from a 2010-aggregated baseline.

Uncertainty

This analysis projected emissions based on the assumption that current semiconductor manufacturing processes continue, and that currently available abatement technologies are used to reduce the resulting F-GHG emissions. It did not model a possible future in which new technologies are applied or F-GHGs use in semiconductor manufacturing is significantly reduced or eliminated. Thus, this analysis may overestimate emissions. In addition, the emission factors used could be revisited in the future, because there are multiple options for emission factor analysis that could affect the results. Finally, the percentages of semiconductor manufacturing emissions that result from chamber cleaning and etching processes were drawn from industry reports; however, these breakdowns could be updated based on the EPA GHGRP data to show a range for 200-mm and 300-mm wafer sizes.

²⁵ For purposes of this report, emissions presented for China include emissions from manufacture in China and Taiwan; however, emissions for these countries were estimated separately because they are treated separately under the WSC and have different industry associations.

²⁶ For the U.S. Semiconductor Industry Association, Japan Electronic and Information Technology Industries Association, and European Semiconductor Industry Association, the baseline year is 1995; for the Korean Semiconductor Industry Association, the baseline year is 1997; and for the Taiwan Semiconductor Industry Association, the baseline is the average of the emission values in 1997 and 1999.

5.2.2.2 Mitigation Options Considered for Semiconductor Manufacturing

Six mitigation technology options were considered for the semiconductor manufacturing sector: thermal abatement, catalytic abatement, plasma abatement, NF₃ 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, Al₂O₃) 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.
- **NF₃ Remote Chamber Clean:** Highly ionized NF₃ is used to clean CVD chambers. This process is very efficient (using ~98% of the gas in a process), resulting in lower emissions on a mass and CO₂ basis than traditional in situ chamber clean processes that use approximately 20% to 50% of the gas in a process and have lower efficiencies (EPA, 2010).
- **Gas Replacement:** Higher GWP gases are replaced with lower GWP gases and in some cases more efficient gases (e.g., C₄F₈ may replace C₂F₆ in a traditional chamber-cleaning process).
- **Process Optimization:** Processes are adjusted to become more efficient, using more gas within the process or inputting less gas into 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 5-14 demonstrates the applicability of each mitigation technology to each process type. While 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 did not model this situation.

Table 5-14: Semiconductor Manufacturing Abatement Options

Fab/Emissions Type	Thermal Abatement	Catalytic Abatement	Plasma Abatement	NF ₃ 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

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.

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 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).

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, oxygen, water, or CH₄) to produce low molecular weight by-products such as 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).

NF₃ Remote Chamber Clean

NF₃ remote chamber clean is an alternative cleaning technology that offers the benefit of having a particularly high (~98%) utilization rate of NF₃ (IPCC, 2006 and EPA Subpart I of the Greenhouse Gas Reporting Program), resulting in relatively low emissions compared with traditional chamber cleans. NF₃ remote clean systems dissociate NF₃ 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, F₂, and other gases, most of which are removed by facility acid scrubber systems. The use of NF₃ 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 NF₃ remote clean systems will differ for new and old fabs because of the “readiness” for NF₃ remote clean installation. “Readiness” consists of having the current infrastructure (e.g., duct work, hookups) for system installation. It was assumed that old fabs 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.

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 C₄F₈ to replace C₃F₈ or C₂F₆. In addition, the replacement gas (C₄F₈) is often used/consumed more efficiently during CVD chamber cleaning than the original gas C₂F₆ or C₃F₈, which, combined with the differences in GWP, yields lower emissions.

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 affecting 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 \$121,370; it was assumed that old fabs incur this cost, while new fabs do not implement this technology because of their assumed use of NF₃ remote clean for most of clean processes.

5.2.2.3 Model Facilities

The analysis considers two types of facilities, distinguished generally by the size of wafer manufactured:

- New Facilities: Facilities that manufacture wafers that are 300 mm or larger. These types of facilities tend to have more complex processes, particularly for plasma etching, which can lead to higher emissions. These facilities have a high likelihood of using remote chamber clean processes and are more likely to have abatement installed. Using data from Subpart I of EPA's GHGRP and information from the World Fab Forecast, average new facility emissions, size of facility in terms of manufactured wafer area, and the percentage of etch versus clean emissions were determined. For purposes of this analysis, these characteristics of the facility did not change over time.
- Old Facilities: Facilities that manufacture wafers that are 200 mm or smaller. These types of facilities tend to have fewer complex processes and rely on more traditional in situ chamber clean processes as well as remote clean processes. They also have more physical space limitations in facility subflooring, which can limit the use of abatement systems. Using data from Subpart I of EPA's GHGRP and information from the World Fab Forecast, average new facility emissions, size of facility in terms of manufactured wafer area, and the percentage of etch versus clean emissions were determined. For purposes of this analysis, these characteristics of the facility did not change over time.

5.2.2.4 Technical and Economic Characteristics Summary

Table 5-15 and Table 5-16 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 5-15 for each process as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency.

Table 5-15: Technical Effectiveness Summary for Newfabs (Constant Over Time)

Abatement Measure	Etch (54%)		Clean (46%)		Reduction Efficiency	Technical Effectiveness
	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration		
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 5-16: Technical Effectiveness Summary for Old fabs (in 2020)

Abatement Measure	Etch (34%)		Clean (66%)		Reduction Efficiency	Technical Effectiveness
	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration		
Thermal abatement	30%	90%	30%	15%	95%	15%
Catalytic abatement	30%	5%	0%	5%	99%	1%
Plasma abatement	30%	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 5-15 and Table 5-16 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 NF₃ remote systems in place less market share would go to gas replacement and process optimization.

The technical effectiveness estimates were then multiplied by the share of total emissions for each facility type to estimate the abatement potential achievable under each abatement measure.

Table 5-17 presents a summary of the engineering cost data for each of the mitigation technologies.

Table 5-17: Engineering Cost Data on a Facility Basis—Semiconductor Manufacturing

Abatement Option	Project Lifetime (years)		Capital Costs (2010 USD)		Annual Costs (2010 USD)		Abatement Amount (tCO ₂ e)	
	New	Old	New	Old	New	Old	New	Old
Thermal abatement	7	7	\$12,551,949	\$6,275,974	\$723,935	\$361,967	33,724	8,143
Catalytic abatement	7	7	\$15,203,729	\$7,601,864	\$957,481	\$501,109	502	358
Plasma abatement	7	7	\$3,994,685	\$1,997,342	\$114,134	\$57,067	492	350
NF ₃ remote clean	22	11	\$3,307,599	\$10,127,096	\$1,337,192	\$3,714,600	2,784	2,181
Gas replacement	22	11	n/a	\$1,539,176	n/a	\$83,783	n/a	1,414
Process optimization	22	11	n/a	\$121,370	n/a	(\$168,359)	n/a	992

5.2.2.5 Sector-Level Trends and Considerations

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 emission reduction goals. These trends are described below.

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 chip production (e.g., 150 mm to 200 mm to 300 mm to 450 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 with 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 NF₃ remote-clean technologies that result in lower emissions on a CO₂e basis than traditional older C₂F₆- or C₄F₈-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 comes online using 450-mm wafers, it is expected they will continue to use NF₃ remote clean technologies, abatement, and more advanced etch processes.

In the 1990s, the absence of emission control measures, rapid growth of the semiconductor industry (11% to 12% per year through the late 1990s), and increasing complexity of microchips could have potentially resulted in significantly increased future emissions from semiconductor manufacturing. In response, the EPA and the U.S. semiconductor industry launched a voluntary partnership to reduce F-GHG emissions in 1996. In 1999, the U.S. partnership catalyzed a global industry commitment through the World Semiconductor Council (WSC). Most WSC member countries—the United States, European Union, Japan, South Korea, and Taiwan²⁷—voluntarily committed to reduce HFC, PFC, NF₃, and SF₆ emissions to 90% of 1995 levels by 2010.²⁸ This emission reduction goal was met in 2010. Achievement of the 2010 WSC emission reduction goal has occurred in the context of significantly increasing underlying manufacturing activity (WSC, 2011). At the end of the 2010 WSC goal, the member countries, including China, reduced absolute emissions by 32% below the baseline to a level of 2.7 MMTCE, surpassing the 10% reduction target (WSC, 2016). WSC set a subsequent goal for 2020 to implement best practices for new semiconductor fabs to result in a Normalized Emission Rate (NER) of 0.22 kgCO₂e/cm², which is equivalent to a 30% NER reduction from a 2010-aggregated baseline. For the with measures scenario, it was assumed that all of WSC member countries met and maintained the new WSC goal.

5.2.2.6 References

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²⁷ For purposes of this report, emissions presented for China include emissions from manufacture in China and Taiwan; however, emissions for these countries were estimated separately as they are treated separately under the WSC and have different industry associations.

²⁸ For the U.S. Semiconductor Industry Association (SIA), Japan Electronic and Information Technology Industries Association (JEITA), and European Semiconductor Industry Association (ESIA), the baseline year is 1995; for the Korean Semiconductor Industry Association (KSIA), the baseline year is 1997; and for the Taiwan Semiconductor Industry Association (TSIA), the baseline is the average of the emission values in 1997 and 1999.

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- Semiconductor Equipment and Materials Industry. 2018 World Fab Forecast, May 2018 Edition.

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)

5.2.3 Photovoltaic Cell Manufacturing

The photovoltaic (PV) cell manufacturing process can use multiple F-GHGs during production, including NF₃ and the PFCs CF₄ and C₂F₆. PV manufacturing emissions occur during the etching and chamber-cleaning processes. Etching is done on various substrates, including crystalline silicon, amorphous silicon, and other thin films. CF₄ and C₂F₆ are used during the manufacture of crystalline silicon (c-Si) PV cells, and NF₃ is used during the manufacture of amorphous silicon (a-Si) and tandem a-Si/nanocrystalline (nc) silicon PV cells. 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.²⁹

5.2.3.1 Photovoltaic Cell Manufacturing Projections Methodology

UNFCCC-reported, country-specific estimates were not available for any historical years for this emission source. Therefore, the 2006 IPCC Tier 1 methodology (IPCC, 2006) was used to estimate emissions. Activity data for Photovoltaic Manufacturing include maximum design capacities from DisplaySearch database (2009) as well as global installed photovoltaic capacities from EIA (2017). Manufacturing processes of PV cells with c-Si PV cells and a-Si and tandem a-Si/nanocrystalline silicon PV cells use F-GHGs, while other thin film technologies do not. Therefore, this analysis was limited to the c-Si and a-Si PV cell markets. Emission factors were obtained from IPCC (2006) and a EPA-developed NF₃ emission factor.

The Tier 1 basic equation to estimate PFC and NF₃ emissions from photovoltaic manufacturing is as follows:

$$FC_i = EF_i * C_u * C_d \quad (5.8)$$

where:

FC _i =	Emissions of gas <i>i</i> (mass)
EF _i =	Emission factor for gas <i>i</i> (mass/m ²)
C _u =	Fraction of annual plant production capacity utilization (%) ³⁰
C _d =	Annual maximum design capacity of substrate processed (m ²)

The main data sources for this source category were the *DisplaySearch Q4'09 Quarterly PV Cell Capacity Database & Trends Report* (“DisplaySearch database”) (DisplaySearch, 2009) and the *International Energy Outlook 2016* from EIA (2017). The most recent DisplaySearch database available to the EPA, published in 2009, supplied historical (2000 through 2009) and projected (2010 through 2013) annual data through 2013 about all PV manufacturing facilities in the world. This included location (country), type of technology manufactured at a facility (c-Si, a-Si, or other thin film), maximum design capacity (megawatts) of a facility, and in some cases conversion efficiency of the PV technology manufactured at a facility. The *International Energy Outlook* provided global installed PV capacities; these data were used to estimate the global PV cell production data for 2015 through 2040.

As evident by data in the DisplaySearch database, a variety of substrates is used in the production of PV cells, including c-Si, a-Si, and other thin films. Manufacturing processes of PV cells with c-Si PV cells and a-Si and tandem

²⁹ For this analysis, technology market shares were calculated based on a PV market that was assumed to only include c-Si and a-Si technologies, since other thin film technologies do not use fluorinated gases. No correction was made in the global solar manufacturing capacity to account for thin film technologies that do not use fluorinated gases. Projected maximum design capacities also included capacities for c-Si and a-Si only, the two technologies that use PFCs in their manufacturing processes.

³⁰ The fraction of annual plant production capacity utilization (C_u) was assumed to be equivalent to 100%; that is, EPA assumed the maximum design capacity was used.

a-Si/nanocrystalline (nc) silicon PV cells use F-GHGs, while other thin film technologies do not. Therefore, this analysis was limited to the c-Si and a-Si PV cell markets.

Activity Data

Historical

The activity data for emission estimates from PV manufacturing were area (m^2) of PV panels produced, which was derived from maximum design capacities expressed in total peak power production, in megawatts (MW), for each country and the world.

Historical maximum design capacities,³¹ in units of MW, were determined by the following various methods:

- **1990 and 1995:** Maximum design capacities in these years were assumed to be 0 MW because the sector was so small in this time period that any associated manufacturing emissions were assumed to be negligible.
- **2000, 2005, and 2010:** Maximum design capacities by country and for the world in 2000, 2005, and 2010 were extracted directly from the DisplaySearch database (DisplaySearch, 2009).
- **2015:** Maximum design capacities by country and the world in 2015 were estimated from the *International Energy Outlook* (EIA, 2017). It was assumed that the number of total PV panels installed in 2015, calculated based on the difference between the total PV capacity in 2015 and 2014, was the total PV panels produced after taking into account assumed yield, fraction sold, and fraction inventoried. The relationship is provided in the equation below:

$$\text{Maximum Design Capacity (MW)} = \text{Panels Yield} * \\ (1 + \text{Fraction of Panels Inventoried}/\text{Fraction of Panels Sold}) * \text{Total PV Installed (MW)} \quad (5.9)$$

Maximum design capacity was converted to area of produced PV panels (m^2) using technology-specific and time-varying market shares (of substrates types) and average electrical conversion efficiencies for c-Si and a-Si and the expected power produced per unit of solar power absorbed at the Earth's equator at noon (0.001 W/m^2). The equation used for this conversion is as follows:

$$\text{Area of PV Panel Produced (m}^2\text{)} = \text{Maximum Design Capacity (MW)} / [\sum_t (\text{Market Share of Technology } t (\%)) * \text{Average Electrical Conversion Efficiency of Technology } t (\%)) * \text{Expected Power Produced (.001 MW/m}^2\text{)}] \quad (5.10)$$

where t = technology type

Technology market shares³² and average conversion efficiencies³³ were determined using data from the DisplaySearch database (DisplaySearch, 2009). In instances where data were not available to calculate these values (i.e., DisplaySearch information was incomplete or for future years), technology conversion efficiencies and market shares were assumed based on historical data and expert judgment.

³¹ Historical maximum design capacities included maximum design capacities for c-Si and a-Si, the two technologies that use PFCs in their manufacturing processes.

³² For this report, technology market shares were calculated based on a PV market that was assumed to only include c-Si and a-Si technologies.

³³ Technology conversion efficiencies were supplied for some years for both c-Si and a-Si technologies in the DisplaySearch database. For each year this information was supplied, a simple average of the available conversion efficiencies was taken for each technology.

Projected

Projected maximum design capacities,³⁴ in units of MW, were determined by the following methods:

- **2020 through 2040:** World maximum design capacities in 2020 through 2040 were based on the global installed solar generating capacity from EIA's *International Energy Outlook* reference case (EIA, 2017). Projected global installed solar manufacturing capacity in any given year was assumed to be the difference between the solar generating capacity between that year and the previous year.
- **2045 through 2050:** World maximum design capacities in 2045 through 2050 were determined by applying 5-year CAGRs for each time period. These CAGRs of design capacity for the 2040 through 2045 and 2045 through 2050 periods are assumed to be the same as the CAGR of new design capacity from 2035 through 2040.

Country-specific maximum design capacities were determined by applying capacity shares to world maximum design capacity estimates. Country-specific capacity shares were held constant at 2015 levels through 2050.

Maximum design capacity was converted to area of produced PV panels (m^2), using the conversion equation described in the previous section. Technology market shares³⁵ for the a-Si type were assumed to be 20% in 2050 and for the c-Si type were assumed to be 80%. For the in-between years, the technology market shares were interpolated between the years 2015 and 2050. The average conversion efficiencies³⁶ for a-Si type were assumed to increase by 1% every 5 years and were assumed to hold constant for the c-Si type at 2015 levels through 2050.

Emission Factors

Historical and Projected

Area of PV panels (m^2) for each country and the world were converted to emissions (MMTCO₂e) using the emission factors (MMTCO₂e/ m^2) for c-Si and a-Si and the respective market shares of each technology in a given year. CF₄ and C₂F₆ are used during manufacture of c-Si PV cells. Tier 1 emission factors for both of these PFCs for PV manufacturing were obtained from the 2006 IPCC Guidelines (IPCC, 2006).

NF₃ is also used during manufacture of a-Si PV cells; however, no published emission factor for NF₃ used during PV manufacturing was identified. NF₃ is used routinely for cleaning during the manufacture of a-Si PV cells, and the emissions are not negligible, depending on emission abatement practices. Therefore, the EPA developed an emission factor for NF₃ using measured, unpublished NF₃ usage and NF₃ emission data for currently operating a-Si PV manufacturing facilities.³⁷

Emission Reductions in Baseline Scenario

No emission reduction assumptions were incorporated into the base case scenario.

³⁴ Projected maximum design capacities included capacities for c-Si and a-Si, the two technologies that use PFCs in their manufacturing processes.

³⁵ For this report, technology market shares were calculated based on a PV market that was assumed to only include c-Si and a-Si technologies.

³⁶ Technology conversion efficiencies were supplied for some years for both c-Si and a-Si technologies in the DisplaySearch database. For each year this information was supplied, a simple average of the available conversion efficiencies was taken for each technology.

³⁷ In developing an emission factor for NF₃, EPA also considered using NF₃ emissions from the manufacturing stage of solar PV cells, from "Life-Cycle Nitrogen Trifluoride Emissions from Photovoltaics" by Fthenakis et al. (2010). However, given that this emission factor considers abatement, EPA did not use it in this report because this report does not consider abatement in the BAU scenario.

Uncertainty

In developing global projections of PFC emissions from the PV sector, a broad perspective was adapted to determine future capacity for manufacturing PV cells. This forecast was framed by the assumption that the reference case from the *International Energy Outlook* took into account the advances in the use of natural gas and coal along with the use of alternative renewable energy technologies—wind, hydro, geothermal, and solar thermal technologies—that serve as alternatives to both conventional fossil fuels and PV solar. Pressure to develop sources of clean, renewable energy is growing because of the increasing costs and risks of securing traditional energy supplies, the increasing focus on ensuring energy reliability and resilience, the increasing need for more energy as countries like China and India industrialize further, and a growing understanding of the environmental effects of traditional sources of energy.

Although this perspective was useful in framing these projections, many uncertainties surround it. First and foremost are uncertainties in future clean energy and GHG policy, which is one of the main drivers in the use of renewable energy. Demand for renewable energy is highly dependent on the design of such policies, and what these policies will look like and how they will be implemented in some developed nations, as well as developing nations, are still unknown. Additionally, large-scale use of renewable energy to meet base-load power needs will also rely on the use of battery storage, which is still an emerging technology.

Another uncertainty is a longer term shift away from centralized sources of electricity generation to more distributed sources of electricity. It is this distributive benefit that gives solar, over the long term, an advantage relative to other renewable energy sources. This advantage, however, might not become evident in trends until 2025 or sometime thereafter.

Lastly, emissions estimated in these projections do not explicitly consider PFC abatement. Abatement may occur when point-of-use abatement systems are used at a manufacturing facility for PFCs. Additionally, all NF₃ used during chamber cleaning passes through required silane abatement systems for safety purposes, which are capable without modification of abating NF₃ and more capable with some modification. Emission estimates are sensitive to the use of abatement. This sensitivity may be considered in future versions of this report, when more information about this newly emerging sector is available.

5.2.3.2 Mitigation Options Considered for Photovoltaic Cell Manufacturing

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 NF₃ remote chamber clean process. Because of the lack of mitigation cost information specific to PV production, data were drawn from experience reducing emissions from similar processes in semiconductor manufacturing.

- **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, Al₂O₃) 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.
- **NF₃ Remote Chamber Clean:** Highly ionized NF₃ is used to clean CVD chambers. This process is highly efficient (~98%), resulting in lower emissions on a mass and CO₂ basis than traditional in situ chamber-cleaning processes with utilization efficiencies around 20% to 50% (IPCC, 2006).

Thermal Abatement

Thermal abatement systems can be used to abate F-gas 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 results in regulated NO_x emissions.

The total facility capital cost for installing thermal abatement systems is estimated to be \$6.3 million. This estimate includes costs for the systems, the necessary ducting, water recirculation and hookup, and natural gas costs (Fthenakis, 2001; Burton, 2003). The annual operating cost is estimated to be \$361,967 at the facility level. No annual cost savings are associated with using this technology.

Catalytic Abatement

A catalytic abatement system uses a catalyst to destroy or remove F-gas emissions from the effluents of both plasma etching and 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_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 purchasing and installing the abatement systems is estimated to be \$7.6 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 \$501,109. As with other abatement technologies considered in this sector, the use of catalytic abatement systems will not result in annual cost savings.

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-gas molecules that react with fragments of the additive gas (hydrogen, oxygen, water, or CH₄) to produce low molecular weight by-products such as 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 \$2.0 million per facility (Burton, 2003), which covers the purchase and installation of plasma systems. Plasma abatement systems require an annual operation cost of \$1,304 per chamber, which includes general maintenance and use of the systems. Total annual facility costs are \$57,067 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.

NF₃ Remote Chamber Clean

NF₃ remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high (~98%) utilization rate of NF₃ (IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (The stated utilization is based on uses for semiconductor manufacturing; as a result of large gas flows in PV manufacturing, the actual utilization may be lower.) NF₃ remote clean systems dissociate NF₃ 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, F₂, and other gases, most of which are removed by facility acid scrubber systems.

We assumed that PV facilities are not “NF₃ ready”; in other words, these facilities do not have the current infrastructure to handle the direct installation of NF₃ remote systems because this technology is relatively new. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hookups and necessary hardware such as manifolds and valves. The facility cost is estimated to be \$10.1 million. The annual facility cost for NF₃ remote clean is estimated to be \$3.7 million (Burton, 2003). These costs are associated with the purchase of larger volumes of gas (NF₃ versus traditional chamber clean gases), general maintenance, and F₂ scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

5.2.3.3 Model Facilities

The manufacture of PV uses F-GHGs depending on the 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/nanocrystalline (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.

- The model facility 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: CF₄, C₂F₆, and NF₃.³⁸ The emission breakdown for a PV manufacturing facility is estimated to be 25% etch emissions and 75% clean emissions.

The model facility emission breakdown is important because some mitigation technologies are applicable to either both or just one type of manufacturing process.

5.2.3.4 Technical and Economic Characteristics of Options

The mitigation technologies reduce emissions from either etch or chamber clean processes or in some cases both. Table 5-18 presents the applicability and the reduction efficiency of each abatement measure.

Table 5-18: PV Cell Manufacturing Abatement Options

Abatement Option	Applicable	Reduction Efficiency	Information Source
Thermal abatement	Etch and clean	95%	Fthenakis (2001), Beu (2005), and EPA (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)

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 making process-specific estimates of technical applicability and market penetration. We held these assumptions constant for all model

³⁸ Although these gases are used for different PV technologies, for simplicity in this analysis, one general facility producing an unidentifiable PV technology was considered.

years. Table 5-19 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

Table 5-19: Technical Effectiveness Summary—PV Cell Manufacturing

Abatement Measure	Etch (25%)		Clean (75%)		Reduction Efficiency	Technical Effectiveness
	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration		
Thermal abatement	85%	65%	85%	20%	95%	25%
Catalytic abatement	85%	10%	85%	10%	99%	8%
Plasma abatement	85%	25%	0%	0%	97%	5%
NF ₃ remote clean	0%	0%	100%	70%	95%	50%

The technical effectiveness is the weighted average of the abatement measures using the emissions attributed to each process (i.e., 25% etching, and 75% cleaning) as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency for each abatement measure. We then multiplied the technical effectiveness estimates by the share of total emissions to estimate the abatement potential achievable under each abatement measure. Table 5-20 summarizes the information used to estimate the break-even prices in the MAC analysis.

Table 5-20: Engineering Cost Data on a Facility Basis—PV Cell Manufacturing

Abatement Option	Project Lifetime (years)	Capital Costs (2016 USD)	Annual Revenue (2016 USD)	Annual O&M Costs (2016 USD)	Abatement Amount (tCO ₂ e)
Thermal abatement	7	\$6,275,974	\$0	\$361,967.33	4,802
Catalytic abatement	7	\$7,601,864	\$0	\$501,108.98	1,601
Plasma abatement	7	\$1,997,342	\$0	\$ 57,066.92	985
NF ₃ remote clean	25	\$10,127,095	\$0	\$3,714,600.05	9,492

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5.2.4 PFC Emissions from Flat Panel Display Manufacturing

Flat panel display (FPD), namely liquid crystal display (LCD) panels, are components of screens used in consumer electronics, computers, and mobile devices. FPD manufacturing is a relatively new industry that continues to grow as demand for these screens increases. The FPD manufacturing process uses SF₆, PFCs, including CF₄, and NF₃ in the etching and chamber cleaning processes. These F-GHGs are used for CVD cleaning processes and plasma dry etching during manufacture of arrays of thin-film transistors on glass substrates, which switch pixels of LCDs and organic light-emitting diode displays. Various F-GHGs play different roles in each of these processes (e.g., CF₄ is mainly used for etching, while SF₆ and NF₃ are used for both etching and cleaning) and are selected by manufacturers based on their chemical and physical properties and ability to efficiently perform in the process (EPA, 2017). In general, almost all manufacturers used SF₆, NF₃, and CF₄, with a smaller mix of other HFCs and PFCs in some instances.

5.2.4.1 Flat Panel Display Manufacturing Projections Methodology

UNFCCC-reported, country-specific estimates were not available for any historical years for this emission source. Therefore, the 2006 IPCC Tier 1 methodology (IPCC, 2006) was used to estimate emissions. Activity data for flat panel display (FPD) manufacturing include maximum design capacities and input area of manufacturing FPDs from the DisplaySearch database (2009 and 2016). Emission factors were obtained from IPCC (2006) and calculated from CDP-reported data. The Tier 1 basic equation to estimate HFC, PFC, SF₆, and NF₃ emissions from FPD manufacturing is as follows:

$$FC_i = EF_i * C_u * C_d \quad (5.11)$$

where:

FC_i	=	Emissions of gas i (mass)
EF_i	=	Emission factor for gas i (mass/m ²)
C_u	=	Fraction of annual plant production capacity utilization (%) ³⁹
C_d	=	Annual maximum design capacity of substrate processed (m ²)

Activity Data

Historical

The main sources of data for this source category are the DisplaySearch Q4'09 Quarterly FPD Capacity Database & Trends report (“DisplaySearch database”) (DisplaySearch, 2009), and DisplaySearch Q4 2016 Large Area Display Production Strategy Tracker (DisplaySearch, 2016). These databases supply historical and projected annual data through 2017 about all FPD facilities in the world, including location (country), maximum design capacity for substrate processing of a facility (in 1,000 m²), and in some cases the utilized capacity of a facility (percentage). DisplaySearch 2016 provides total input area of large-area displays from each manufacturer for 2012 through 2017.

For 2000 through 2010, “utilized capacity (m²) of FPD area produced” was the activity data used to estimate emissions. The activity data were derived from maximum design capacity expressed in area (1,000 m²) for each country and the world. Maximum design capacity was converted to utilized capacity (m²) by applying a utilized capacity factor (%). For simplicity, a single, global average utilized capacity factor of 88% was applied to all countries and to the world for all years. This factor was derived by taking a simple average of the world utilized

³⁹ EPA assumed that C_u is equivalent to 88% for 1990 through 2010.

capacity factors (percentage) for all years provided in the DisplaySearch FPD database (DisplaySearch, 2009).⁴⁰ For 2012 through 2017, the “input area of manufactured FPDs (m²)” was the activity data used to estimate emissions. Total input area for 2012 through 2017 was estimated by adjusting the large-area panel input area from DisplaySearch (2016) based on the share of small and medium panels from each manufacturer in 2012 from DisplaySearch (2009).

Total maximum design capacities were determined by the following various methods:

- **1990, 1995:** Total world maximum design capacities in 1990 and 1995 were determined by applying 5-year global CAGRs for each period. These 5-year global CAGRs were assumed based on expert judgment about past demand in the FPD market.

Using the world maximum design capacity estimate for each year and country-specific shares of world capacity (“capacity shares”), the EPA determined country-specific CAGRs for each 5-year interval using the following equation:

$$\text{Country5YearCAGR}_i = \left[\frac{\text{WorldManufacturedCapacity}(Y_f) * \text{CountryShare}_i(Y_f)}{\text{WorldManufacturedCapacity}(Y_o) * \text{CountryShare}_i(Y_o)} \right]^{1/5} - 1 \quad (5.12)$$

where:

- Y_f = Future year
- Y_o = Initial year
- i = Country index

Country-specific capacity shares for 1990 and 1995 were assumed to be equivalent to the 2000 country-specific capacity shares, determined by using country and world capacity data extracted from the DisplaySearch database (DisplaySearch, 2009).

Maximum design capacity was back casted for each country for the years 1990 and 1995 by applying a country-specific 5-year CAGR to maximum design capacity in the appropriate adjacent time frame.

- **2000, 2005, and 2010:** Total maximum design capacities were determined by country and for the world in 2000, 2005, and 2010 directly from the DisplaySearch database (DisplaySearch, 2009).

As noted above, once total maximum design capacities were determined for each country and the world for the 1990 through 2010 time series, these values were converted to utilized capacity (m²) using a world average utilized capacity factor.

- **2015:** Total large-area display input area was obtained from DisplaySearch2016 and adjusted to account for small and medium area display area. The input area used in this time series was the same as the “utilized capacity” in historical time series.

Projected

- **2020 through 2050:** Total display input area was determined starting from the last available DisplaySearch2016 data and grown using the historical annual growth rate of 8.5%, the average of the growth rates between 2012 and 2017, until 2025. For the time frame of 2025 through 2050, a more conservative growth rate of 4.3% was applied, representing half of the growth rate used until 2025.

⁴⁰ In the DisplaySearch FPD database, capacity utilizations (%) were only available for the years 2005 through 2010. The capacity utilization provided for the world in each of these years was simply averaged together to get the capacity utilization factor used in this analysis (88%). While the DisplaySearch databases provided some country-specific capacity utilizations for specific fabs in a country, there were many gaps in these data. Therefore, using the database may have led to an underestimation of actual emissions.

Emission Factors

Historical and Projected

To determine emissions for each country, the EPA converted the total utilized capacity and total input area (m^2) to PFC, HFCs, NF₃, and SF₆ emissions (MMTCO₂e) using:

- IPCC Tier 1 emission factors for PFCs, NF₃, and SF₆ (MMTCO₂e/ m^2) (IPCC, 2006) and
- the calculated emission factor for HFC using emission data reported to the CDP (formerly the Carbon Disclosure Project). The EPA used reported emission data for one representative facility to develop an HFC emission factor (MMTCO₂e/ m^2), which was applied for each country.

Emission Reductions in Baseline Scenario

Without incentives and or emission targets, it was assumed that the FPD sector does not employ additional abatement technologies beyond what had been installed as of 2012 (TTLA, 2012). To reduce emissions, this sector may employ abatement technologies, including fueled combustion, plasma and catalytic technologies explicitly intended for F-GHG abatement.

Uncertainty

These global emission projections are highly sensitive to the assumption that China's domestic demand for FPDs will substantially increase in the future (DisplaySearch, 2016), thereby increasing Chinese domestic capacity and production of FPDs and hence increasing emissions. If actual domestic demand in China varies in the future, China's large contribution to global emissions may change.

5.2.4.2 Mitigation Options Considered for Flat Panel Display Manufacturing

We identified six mitigation technology options for the FPD manufacturing sector: central abatement, thermal abatement, catalytic abatement, plasma abatement, NF₃ remote chamber clean, and gas replacement.

- **Central Abatement:** These large-scale abatement systems are generally located on the roof of facilities and are applicable to etch emissions (SF₆).
- **Thermal Abatement:** These point-of-use (POU) abatement systems, which 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, Al₂O₃) 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.
- **NF₃ Remote Chamber Clean:** Highly ionized NF₃ is used to clean CVD chambers. This process is highly efficient (using ~98% of the gas in a process), resulting in lower emissions on a mass and CO₂ basis than traditional in situ chamber clean processes that use approximately 20% to 50% of the gas in a process (IPCC, 2006).
- **Gas Replacement:** Higher GWP gases are replaced with lower GWP gases.

Central Abatement

Central abatement systems (CASs) have begun to be designed and used to handle the generally high gas (SF₆) 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 few 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 \$4.9 million. The annual O&M cost, which includes items such as utilities and parts, is estimated to be \$2.8 million for a facility. No revenues are generated from using a CAS.

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 \$6.3 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 \$361,967 at the facility level. No annual savings are associated with using this technology.

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 noted for thermal abatement systems, thus 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 \$7.6 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 \$501,107. As with other abatement technologies considered in this sector, the use of thermal abatement systems will not result in annual savings.

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, oxygen, water, or CH₄) to produce low molecular weight by-products such as 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-gas molecules (Motorola, 1998).

The capital cost for plasma abatement systems is estimated to be \$1.9 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 \$1,304 per chamber, which includes general maintenance and use of the systems. The total annual facility cost is \$114,114 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.

NF₃ Remote Chamber Clean

NF₃ remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high utilization rate of NF₃ (~98%; IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (Note: The stated utilization is based on uses in semiconductor manufacturing; as a result of large gas flows in FPD manufacturing, the actual utilization may be lower.) NF₃ remote clean systems dissociate NF₃ 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, F₂, and other gases, most of which are removed by facility acid scrubber systems. The use of NF₃ remote clean systems is much more prevalent in new facilities because the technology was not available when many old facilities were constructed.

We assumed FPD facilities are not “NF₃ ready”; in other words, these facilities do not have the current infrastructure to handle the direct installation of NF₃ remote systems because this technology is relatively new. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hookups and necessary hardware such as manifolds and valves. The facility cost is estimated to be \$10.1 million. The annual facility cost for NF₃ remote clean is estimated to be \$3.7 million (Burton, 2003). This cost is associated with the purchase of larger volumes of gas (NF₃ vs. traditional chamber clean gases), general maintenance, and F₂ scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

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 NF₃ to replace SF₆.

Facilities replacing SF₆ with NF₃ incur an estimated capital cost of \$1.3 million for items such as gas hookups and implementation. Annual savings for this option result from the lower cost of the replacement gas and are estimated to be \$47,611, based on the incremental cost of the gases and the average amount of gas consumed per facility. Gas replacement has no operational costs.

5.2.4.3 Model Facilities

The manufacture of flat panels uses F-gases. 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.

- The model facility represents an average flat panel display manufacturing facility. The average manufacturing capacity (DisplaySearch, 2009) of a fabrication lab is 760,839.9 m² and is estimated to have 25 tools with four chambers. The facility only uses CH₄, SF₆, and NF₃. Model facilities are NF₃ remote clean ready. The emission breakdown for a FPD manufacturing facility is estimated to be 23% etch emissions and 77% clean emissions.

The model facility emission breakdown is important because some mitigation technologies are applicable to either both or just one type of manufacturing process.

5.2.4.4 Technical and Economic Characteristics Summary

This section describes the mitigation options in detail and includes technical and economic data that were used to calculate the break-even price and reduction potential for each option.

Table 5-21 presents the reduction efficiency and the applicability of each mitigation technology to emissions from a type of process (etch and/or clean).

Table 5-21: FPD Manufacturing Abatement Options

Abatement Option	Applicable Process Emission Type(s)	Reduction Efficiency	Information Source
Central abatement	Etch	77%	CDM project #3333
Thermal abatement	Etch and clean	95%	Fthenakis (2001), Beu (2005), and EPA (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

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 5-22 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

Table 5-22: Technical Effectiveness Summary—Flat Panel Display Manufacturing

Abatement Measure	Etch (23%)		Clean (77%)		Reduction Efficiency	Technical Effectiveness
	Technical Applicability	Market Penetration	Technical Applicability	Market Penetration		
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 emission 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 that 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 emission reductions that is technically achievable.

Table 5-23 summarizes the engineering cost data and abatement potential for each abatement option considered in this analysis.

Table 5-23: Engineering Cost Data on a Facility Basis—Flat Panel Display Manufacturing

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	\$4,939,147	\$0	\$2,803,407	5,889
Thermal abatement	7	\$6,275,974	\$0	\$361,967	32,749
Catalytic abatement	7	\$7,601,864	\$0	\$501,109	9,600
Plasma abatement	7	\$1,997,342	\$0	\$114,134	3,167
NF ₃ remote clean	21	\$10,127,096	\$0	\$3,714,600	12,029
Gas replacement	21	\$1,298,791	\$47,611	\$0	2,427

5.2.4.5 References

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5.2.5 SF₆ Emissions from Electric Power Systems

SF₆ is used as both an arc-quenching and insulating medium in electrical transmission and distribution equipment. SF₆ emissions from electrical equipment used in transmission and distribution systems occur through leakage and handling losses. Leakage losses can occur at gasket seals, flanges, and threaded fittings and are generally larger in older equipment. Handling emissions occur when equipment is opened for servicing, SF₆ gas analysis, or disposal. The manufacture of equipment for electrical transmission and distribution can also result in SF₆ emissions, but this source is not included in this report.⁴¹

Several factors affect SF₆ emissions from electrical equipment, including the type and age of SF₆-containing equipment, and the handling and maintenance protocols used by electric utilities. Historically, approximately 20% of total global SF₆ sales have been attributed to electric power systems, where the SF₆ is believed to have been used primarily to replace emitted SF₆. Approximately 60% of global sales have gone to manufacturers of electrical equipment, where the SF₆ is believed to have been mostly banked in new equipment (Smythe, 2004).

5.2.5.1 Electric Power Systems Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this category, when available. The 2006 IPCC Tier 1 methodology (IPCC, 2006) was not well suited to estimate emissions from electric power systems given the type of data available on global SF₆ use. Instead, if country-reported emission estimates were not available for any historical years, estimates were calculated based on a methodology derived from an equation in the IPCC Good Practice Guidance (IPCC, 2000). Activity data included a RAND survey of global SF₆ sales to electric utilities and equipment manufacturers from Knopman and Smythe (2007), estimates of net electricity generation and consumption from EIA's International Energy Outlook (2017), and a report of emissions from equipment use and decommissioning in the European Union from Ecofys (2005). The successful attainment of developed country SF₆ reduction goals are accounted in the emission projections. Methods contained in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) were not well suited to estimate emissions from electric power systems given the type of data available on global SF₆ use. Instead, estimates were calculated using the following equation, which was derived from the equation for emissions in the IPCC Good Practice Guidance (IPCC, 2000):

$$\text{Emissions} = \text{SF}_6 \text{ purchased to refill existing equipment} + \text{nameplate capacity of retiring equipment} \quad (5.13)$$

This equation holds true regardless of whether the gas is released or recovered from retiring equipment. Recovered gas is used to refill existing equipment, lowering the amount of SF₆ purchased by utilities for this purpose.

The primary driving factors for determining historical emissions in the electric power systems methodology are the source data from UNFCCC, RAND, and EIA. For determining projected emissions, the primary factor in determining these estimates is the methodology for the projection calculation, described in-depth below.

Activity Data

Historical

RAND, EIA, and Ecofys data were used to estimate historical emissions in the absence of country-level estimates from UNFCCC. First, total world SF₆ emissions were estimated using data from the 2007 RAND survey (Knopman and Smythe, 2007). The data included total gas purchases by utilities and equipment manufacturers

⁴¹ Although these emissions were not explicitly estimated in this study, some A1 countries report emissions from the manufacture of equipment for electrical transmission and distribution equipment manufacture within this source category. In these cases, this source category includes these emissions.

from 1961 through 2006 (believed to include all SF₆-consuming countries except Russia and China). From these data, the two components of the above emission equation were calculated using the following assumptions:

1. SF₆ emitted by utilities in a given year is approximately equal to SF₆ purchased to refill existing equipment in a given year.^{42,43}
2. The nameplate capacity of retiring equipment in a given year was assumed to be equal to 77.5% of the amount of gas purchased by electrical equipment manufacturers 30 years previous (e.g., in 1990, the nameplate capacity of retiring equipment is equal to 77.5% of the gas purchased by original equipment manufacturers in 1960).⁴⁴ The remaining 22.5%⁴⁵ was assumed to have been emitted at the time of manufacture.

The RAND survey data were adjusted to include sales for China and Russia, which were not included in the survey. To make this adjustment, it was assumed Russian and Chinese SF₆ sales were proportional to the net electricity consumption of these countries available from EIA (2017). The total sales for the countries represented in the RAND survey were multiplied by the proportion of China's and Russia's net electricity consumption relative to the world net electricity consumption. A 3-year smoothing was applied to the sum of the results to reduce the potential impact of inventory fluctuations on the estimates.

Next, emission estimates were developed for all countries from 1990 through 2006 using the RAND world SF₆ emission totals. Known emission values for the United States, the EU,⁴⁶ and Japan⁴⁷ were subtracted from the world emission total. The remaining emissions were allocated to countries according to each country's share of net electricity consumption to the world net electricity consumption minus consumption from the United States, the EU, and Japan (EIA, 2017).

For 2010 historical emissions, each country's 2006 emission estimates were extrapolated based on the change in world net electricity consumption from 2006 through 2010, as provided by EIA (2017). It was necessary to use extrapolation for 2010 emissions because RAND ceased publication of its survey in 2007, so 2006 was the last year for which RAND survey data were available.

Projected

Global emission projections were developed using the following approaches:

- Projections were extrapolated from a country's last reported estimate using a growth rate based on estimates from the last 5 years of reported estimates. The extrapolation method was used for the United States based on the 2015 estimate (EPA, 2016) and for EU countries based on the 2015-reported estimates from Ecofys (2005). The growth rates reflect a declining growth rate in emissions and hence a decline in forecasted emissions for these countries.

⁴² Communications with electrical equipment manufacturers indicated that beginning in the late 1990s, a small but increasing fraction of new equipment was being filled with gas purchased by utilities rather than by equipment manufacturers. In this analysis, EPA assumed that in 1999 1% of new equipment was filled using gas purchased by utilities and by 2003 this fraction had grown to 5%. This assumption has the effect of decreasing estimated global refills and emissions by 11% in 2003.

⁴³ See the country-by-country emissions section for information on how emissions were estimated for Russia and China.

⁴⁴ The volume of SF₆ sold for use in new equipment before 1961 was assumed to have increased linearly from 0 tons in 1950 to 91 tons in 1961, the first year for which the RAND survey has data.

⁴⁵ The 22.5% emission rate is an average of IPCC SF₆ emission rates for Europe and Japan before 1996 (IPCC, 2000).

⁴⁶ EU emissions were based on those provided for equipment use and decommissioning in *Reductions of SF₆ Emissions from High and Medium Voltage Electrical Equipment: Final Report to CAPIEL* (Ecofys, 2005). The Ecofys study relied on bottom-up estimates of emission rates and of the SF₆ bank in equipment, both of which varied by region and over time. A newer report was published by Ecofys (2010); however, specific country-level estimates were not presented in a table format.

⁴⁷ Historical emissions data for Japan used in this analysis were available through the UNFCCC flexible query system (UNFCCC, 2016).

- For Japan, Canada, Australia, the rest of Europe, Hong Kong, Singapore, and Eurasia, projections were based on holding the 2006 emission estimate constant for the remainder of the time series. The underlying assumption for this approach was that any emissions associated with system growth are expected to be offset by decreases in the equipment's average SF₆ capacity and emission rate as new, small, leak-tight equipment gradually replaces old, large, leaky equipment. With regard to Japan, while the SF₆ bank in Japan is expected to grow substantially in the future, it was assumed that, in addition to adoption of newer equipment with smaller SF₆ capacity, continued reduction measures would maintain historical emission levels through the time series (Yokota et al., 2005).
- For all other countries, primarily developing countries, projections were extrapolated from the 2010 values using the country's electricity generation growth rate (EIA, 2017). Country-specific growth rates were used when available; when not available, region-level growth rates were used. This approach was used for most developing countries based on the assumption that these countries began to install SF₆ equipment relatively recently. Consequently, as infrastructure expands, emissions from developing countries are anticipated to grow at the same rate as country- or region-specific net electricity generation projections.

Emission Reductions in Baseline Scenario

Since the mid to late 1990s, various developed countries have implemented voluntary (and in some cases mandatory) programs aimed at reducing SF₆ emissions from electric power systems. These countries include the United States, Japan, and countries in the EU. The successful attainment of developed-country SF₆ reduction goals is accounted for in the emission projections; however, the EPA did not consider any enhanced future mitigation from these programs beyond existing levels.

Uncertainties

In developing emission estimates for this source, the EPA used multiple international datasets and IPCC guidance. The robustness of the bottom-up estimates is believed to have improved since the previous EPA-published report (EPA, 2012) because of the use of updated RAND and EIA data in this version of the report. Nevertheless, this analysis is subject to a number of uncertainties that affect both global- and country-specific emission estimates, particularly estimates for countries other than the United States, Japan, and the EU.

First, the SF₆ producers represented in the RAND survey do not represent 100% of global SF₆ production and consumption. The EPA accounted for unreported Russian and Chinese SF₆ production, consumption, and emissions by assuming a relationship between net electricity consumption and SF₆ emissions. However, this assumption is subject to uncertainty. One source of this uncertainty is the fact that net exports from or imports into Russia and China affect the relationship between SF₆ consumption and net electricity consumption in the rest of the world. Net exports from Russia and China would make the “consumption factor” (SF₆ consumption/net electricity consumption) in the rest of the world appear to be smaller than it actually is, while net imports would have the opposite impact. Information from manufacturers of electrical equipment indicates that exports from Russia and China have fluctuated over time, peaking around the year 2000 and declining more recently. Thus, the apparent dip in global emissions between 1995 and 2000, and the subsequent rise between 2000 and 2005, may be partly an artifact of these export trends rather than purely a result of changes in emissions from electric power

systems.⁴⁸ Another source of uncertainty is that the relationship between SF₆ emissions and net electricity consumption varies from country to country, even when imports and exports are properly accounted for.⁴⁹

Second, the RAND survey's attribution of SF₆ sales to particular end uses is also uncertain, because SF₆ producers frequently sell to distributors rather than directly to end users. Although producers would be expected to have a reasonably good understanding of their markets, this understanding is not always accurate. Thus, some of the SF₆ sales that the survey attributed to utilities could have actually been attributed to other uses or vice versa.

Third, the typical lifetime of electrical equipment, and therefore the amount of equipment that is now being retired, is uncertain. This analysis used a lifetime of 30 years; however, other publications have estimated the lifetime at 40 years. The typical lifetime assumption is important because the amount of equipment manufactured 30 years ago is considerably larger than the amount of equipment manufactured 40 years ago. If the average lifetime of equipment was assumed to be less than 30 years, then the estimate of 2006 global emissions would decrease.

Fourth, for countries other than the EU, Japan, and countries that have reported to the UNFCCC, the EPA assumed that each country's share of past and current global emissions is directly proportional to that country's share of past and current global net electricity consumption. In fact, as noted above, the relationship between emissions and electricity consumption varies between regions and over time, particularly as regions make efforts to reduce their emission rates. Thus, there is an associated uncertainty in the allocation of global emissions to individual regions within this analysis.

Fifth, emission estimates based on RAND sales data do not include SF₆ emissions from electrical equipment manufacturing. However, some of the UNFCCC-reported data that were used do include emissions from the manufacture of electrical equipment.

Finally, emission projections were based on the assumption that emissions in developing countries will increase with increasing net electricity generation. However, the application, design, and maintenance of equipment all affect equipment banks and emission rates. These factors may change over time, which may alter the trends observed to date. For example, switchgear dimensions have changed since the 1970s, resulting in a reduction in the amount of SF₆ required in switchgear (Ecofys, 2010).

5.2.5.2 Mitigation Options Considered for Electric Power Systems

This analysis considers six abatement options for this sector: SF₆ recycling, leak detection and repair (LDAR) using a thermal imaging camera, LDAR using a handheld gas detector, equipment replacement, the use of SF₆ free gas insulated equipment, and improved SF₆ handling. Refurbishing existing equipment has been considered previously in this analysis; however, industry experts have stated that this is no longer a common practice in the field.

For the purposes of this analysis, four distinct emission streams were analyzed for the sector—improper handling of SF₆; venting during equipment maintenance and disposal; periodic leakage from equipment; and chronic leakage from equipment. Each abatement option can only target one emission stream. Two emission

⁴⁸ The bottom-up studies cited above indicate that emissions from this sector declined between 1995 and 2000, and atmospheric studies confirm that emissions declined globally (Maiss and Brenninkmeijer, 2000). Other atmospheric studies indicate that emissions increased after 2000 (Peters et al., 2005). However, the post-2000 increase may be from other sectors (e.g., magnesium or electronics).

⁴⁹ S. Reiman and M. Vollmer of EMPA have performed a preliminary analysis of this relationship, comparing the SF₆ emissions reported through national inventories with the net electricity consumption reported by EIA. They find that the ratios between these two values vary by more than a factor of 10.

streams—chronic leakage from equipment and periodic leakage from equipment can be mitigated by two abatement options. Specifically, chronic leakage from equipment can be mitigated by either equipment replacement or the use of SF₆ free gas insulated equipment and periodic leakage from equipment can be mitigated by either of the two leak detection and leak repair options (thermal imaging camera and hand-held gas detectors).

SF₆ Recycling

This option involves transferring SF₆ from electrical equipment into storage containers during equipment servicing or decommissioning so that the SF₆ can be reused. Recycling is conducted using an SF₆ reclamation cart (commonly referred to as a gas cart). The gas cart recovers the SF₆ from the equipment and purifies it for future use; the recovered and purified SF₆ 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 the technical literature (International Council on Large Electric Systems, 2005; International Electrotechnical Commission, 2008; Institute of Electrical and Electronics Engineers, 2012). The alternative to using a gas cart is venting the used SF₆ into the atmosphere and then replacing it with fresh SF₆. 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.

- **Capital Cost:** The average total capital costs associated with purchasing gas carts are estimated to be about \$520,000 for the uncontrolled system and \$78,000 for the partially controlled system. The cost per gas cart unit is the same for both systems at approximately \$104,000. Gas carts can range in cost from as low as \$21,000 to as high as \$187,000 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 SF₆ recycling to a greater extent and fewer gas carts are needed across U.S. systems: less than one per system.
- **Annual O&M Costs:** O&M costs are estimated to be \$8,000 for the uncontrolled system and \$22,000 for the partially controlled system. The lower O&M costs for the uncontrolled system are driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual Benefits:** Annual revenue, which was estimated based on the reduction of SF₆ emissions multiplied by the cost per pound of SF₆ gas, is close to \$102,000 for the uncontrolled system and \$2,000 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 91% of its potential; therefore, the potential for reductions is greater. The cost of SF₆ per pound varies regionally and is relatively low in the United States (Rothlisberger, 2018). In addition, partially controlled systems have a significantly lower emission rate, which also results in a comparatively lower annual revenue.

LDAR

LDAR is a two-step process. First, a leak detection technique is used to identify gas leaks from SF₆-insulated equipment. Leak detection methods vary and can involve simple techniques such as using soap and water solutions or more sophisticated techniques such as those requiring detection devices, such as cameras to visualize the source of the SF₆ leaks by exploiting the strong infrared adsorption of SF₆ for detection. 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. Once the leak is repaired, the equipment tends to last months to years without another major leak. SF₆ 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) for this abatement option. Two LDAR options were analyzed, as described below.

Thermal Imaging Camera

This first LDAR abatement option analyzes the use of a thermal imaging camera. Considered the best method for finding leaks on energized equipment, the camera is able to detect even very minor leaks (as small as 0.5 pounds annually). However, some drawbacks of this method are that it requires light from the sun to properly view the leak and an experienced technician (Wolf, 2017).

- **Capital Cost:** Costs associated with purchasing thermal imaging cameras are estimated to be \$21,000 for an uncontrolled abatement system and \$50,000 for a partially controlled system. The cost for a single thermal imaging camera is approximately \$107,000 (Czerepuszko, 2011a).
- **Annual O&M Costs:** O&M costs are estimated to be \$150 for the uncontrolled system and \$3,500 for the partially controlled system. The lower O&M costs for the uncontrolled system are driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual Revenue:** Annual revenue is estimated based on the potential reduction of SF₆ emissions multiplied by the cost per pound of SF₆ gas and is \$2,000 for the uncontrolled system and \$250 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 SF₆ per pound varies regionally and costs significantly less in the United States (Rothlisberger, 2018), the cost of SF₆ per pound is significantly less for the partially controlled system relative to systems in other regions, so less money is saved through reduced emissions.

Handheld Leak Detectors

A handheld detector is a simple, low-cost device that may be used as an alternative to the thermal imaging camera that can be cost prohibitive in developing countries. The detector is used by tracing the entire substation in a continuous path. If a leak is identified, it is verified by blowing shop air into the area of suspected leak and repeating the check of the area using the detector (IonScience, n.d.). This must be done while equipment is in service and cannot be used for decommissioned parts (Wolf, 2017).

- **Capital Cost:** Handheld detectors are estimated to cost \$1,400 in uncontrolled and \$700 in the partially controlled systems, with costs varying based on the assumed potential application of additional detectors that could be utilized. (Ladzinski, 2018).
- **Annual O&M Costs:** For uncontrolled systems, the annual O&M costs are expected to be \$1,600 while in partially controlled systems, they are expected to be \$7,500. This is due to the lower cost of labor in developing countries.
- **Annual Revenue:** The annual revenue is calculated the same way as the LDAR thermal imaging camera option. However, because the handheld detector is less cost prohibitive than the thermal imaging camera, it is assumed to have a higher market penetration, and more than double the percent technical effectiveness than the camera option for the uncontrolled system, resulting in annual revenues of \$7,600. For the partially controlled, the annual revenue is estimated at \$250, the same as the LDAR thermal imaging camera method.

Equipment Replacement

Unlike Equipment replacement is an option by which chronic leaking equipment is identified and replaced with new and less leak prone equipment. Engineering design changes have reduced the amount of SF₆ necessary for the operation of switchgear and increased the tightness of equipment, resulting in smaller leakage amounts and less frequent leakage over time. Replacing gas insulated equipment is a costly and timely option but eliminates the worst performing breakers and helps to increase system reliability.

- **Capital Cost:** Assuming the replacement of a total of eight 145 kV breakers annually, costs associated with equipment replacement are estimated to be \$2,9 million for both an uncontrolled system and partially controlled system. The estimated cost to replace a single 145 kV circuit breaker is estimated to be \$350,000 (based on a range of \$200,000 for a 120 KV breaker up to \$500,000 for a 345-kV breaker, as provided by McNulty and Jasinski [2012]).
- **Annual O&M Costs:** No incremental O&M costs are assumed to be associated with this option.
- **Annual Revenue:** Annual revenue, which was estimated based on the reduction of SF₆ emissions multiplied by the cost per pound of SF₆ gas, is \$18,000 for the uncontrolled system and \$2,000 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has a higher SF₆ rate compared to developing countries, and therefore more emissions to abate relative to the partially controlled systems; therefore, the potential for reductions is greater. In addition, the cost of SF₆ per pound is significantly less for the partially controlled system, so less money is saved through reduced emissions.

SF₆-free Gas Insulated Equipment

New circuit breaker technology has been developed that uses alternative gases to SF₆ that have lower or no global warming potential. Traditional gases such as dry air, nitrogen, CO₂ and related mixtures are low global warming but are limited in their dielectric strength as compared to SF₆ (Kieffel et al., 2015). A class of g³ mixtures based on 3M™ Novec™ fluids have a higher GWP of less than 500 compared to the traditional gases (yet significantly lower GWP as compared to SF₆), their dielectric properties are stronger (Kieffel et al., 2015). While not commercialized yet in the United States, early adopters are beginning to transition to g³ alternatives in Europe (GE, 2017). Vacuum is a technology that does not use any SF₆ and is well established in the medium voltage class of equipment; in 2015, the technology entered pilot application for high voltage equipment at 145 kV (Kieffel et al., 2015). Vacuum technology for high voltage equipment is beginning to enter the market (Rak, 2017b; Glaubitz, 2017; Ecofys, 2018). This option is based on similar assumptions to the equipment replacement option. For the purpose of this analysis, vacuum technology was assumed to be the replacement technology. Vacuum-based technology is also considered an option in Europe and Japan for partially controlled systems and was included in our analysis for this abatement option.

- **Capital Costs:** The newer SF₆-free gas insulated equipment is currently more expensive than the traditional breakers that contain SF₆. Assuming the replacement of a total of eight 145 kV breakers annually, the capital cost for this equipment in each of the three model facility systems is \$4.3 million. The estimated cost to replace a single 145 kV circuit breaker is estimated to be \$550,000. It is assumed that the technology is 50% more expensive than a traditional SF₆ breaker, and the McNulty and Jasinski (2012) capital cost estimate is used as the basis. It is assumed that a team of four field personnel require one week (40 hours) of labor time to install one breaker.⁵⁰ Information on costs is limited, and in lieu of a source on high voltage replacement costs, medium voltage capital costs were referenced. Ecofys (2018) reports that SF₆ free medium voltage (up to 36 kV) GIE can be 30 to 50% more expensive than regular SF₆ breakers.
- **Annual O&M Costs:** Equipment maintenance is not necessary until at least 25 years after installation (Rak 2017b; Glaubitz, 2017). No incremental O&M costs are assumed to be associated with this option.
- **Annual Revenue:** Annual revenue for the uncontrolled systems will be \$18,000, \$2,000 for the partially controlled-United States system, and \$1,000 for the partially controlled-Europe/Japan system. These

⁵⁰ Planning hours associated with the replacement, which may include time needed to receive necessary approvals for the installation were not quantitatively considered. Any prior effort needed by a utility to accept this option, such as a smaller pilot-scaled study of the technology, also were not quantified.

estimates are based on the technical applicability of this technology and the potential for it to reduce the emissions assumed for each model facility.

Improved SF₆ Handling

This option involves improving the procedures and techniques for handling SF₆, 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) SF₆ 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) a technician accidentally vents SF₆. Improving SF₆ 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. SF₆ 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).

- **Capital Cost:** The capital cost associated with improved SF₆ handling is estimated to be \$15,000 for both the uncontrolled system and the partially controlled system. This capital cost consists entirely of purchasing adapter kits, which are estimated to cost \$1,500 each (middle of cost range provided by Rothlisberger [2011a]).
- **Annual O&M Costs:** O&M costs are estimated to be \$400 for the uncontrolled system and \$3,000 for the partially controlled system. The lower O&M cost for the uncontrolled system is 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 SF₆ emissions multiplied by the cost per pound of SF₆ gas, is \$136,000 for the uncontrolled system and \$7,000 for the partially controlled system.

5.2.5.3 Model Facilities

The analysis considers several possibilities for the maintenance and SF₆ 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:

- Partially controlled system—United States: Abatement options have been partially to fully applied in the United States. The partially controlled system represents an EPS containing SF₆-insulated equipment located in the United States.
- Partially controlled system—Europe/Japan: In Europe and Japan, abatement options are close to fully implemented, except for the use of SF₆ free gas insulated equipment, which only recently began to gain market momentum, and represents an opportunity for further abatement for these systems.
- Uncontrolled system: In contrast, abatement options have only been minimally applied or not applied at all in most developing countries (Czerepuszko, 2011a; North China Grid Company [NCGC], 2010). Therefore, the uncontrolled containing SF₆-insulated equipment located in a developing country, which for this analysis would mean any country outside of Europe, Japan, and the United States. EPS containing SF₆-insulated equipment located in a developing country, which for this analysis means any country outside of Europe, Japan, and the United States.

5.2.5.4 Technical and Economic Characteristics Summary

Table 5-24 shows the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness for each model facility type. The technical effectiveness parameter represents the percentage reductions achievable by each technology/facility type combination.

Table 5-24: Technical Effectiveness Summary—Electric Power Systems

Abatement Option	Model Facility Type	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
SF ₆ recycling	Uncontrolled	30%	100%	90%	27%
	Partially controlled (US)	10%	100%	90%	9%
LDAR (Thermal Imaging Camera)	Uncontrolled	5%	20%	50%	1%
	Partially controlled (US)	5%	50%	50%	1%
LDAR (Handheld Leak Detector)	Uncontrolled	5%	80%	50%	2%
	Partially controlled (US)	5%	50%	50%	1%
Equipment Replacement	Uncontrolled	10%	50%	95%	5%
	Partially controlled (US)	20%	50%	95%	10%
SF ₆ -free Gas Insulated Equipment	Uncontrolled	10%	50%	95%	5%
	Partially controlled (US)	20%	50%	95%	10%
	Partially controlled (Europe/Japan)	100%	25%	95%	24%
Improved SF ₆ Handling	Uncontrolled	40%	100%	90%	36%
	Partially controlled (US)	40%	100%	90%	100%

Table 5-25 summarizes the economic characteristics of each option. More details on the data sources and assumptions used to develop these costs are described below.

Table 5-25: 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 ₂ e)
SF ₆ recycling	15	\$520,156	\$101,919	\$7,592	44,678
		\$78,023	\$1,716	\$20,097	2,048
LDAR (Thermal Imaging Camera)	5	\$20,700	\$1,887	\$151	827
		\$49,615	\$238	\$3,468	284
LDAR (Handheld Leak Detector)	5	\$1,387	\$7,550	\$1,557	3,309
		\$693	\$238	\$7,458	284
Equipment Replacement	40	\$2,886,599	\$17,930	-	7,860
		\$2,844,205	\$1,811	-	2,161
SF ₆ -free Gas Insulated Equipment	50	\$4,328,671	\$17,930	-	7,860
		\$4,373,246	\$1,811	-	2,161
Improved SF ₆ handling	1	\$4,369,910	\$1,029	-	1,228
		\$14,671	\$135,893	\$358	59,570

The cross-cutting engineering cost inputs used for the assessment of all abatement options are supplied in Table 5-26 (all costs in 2010 USD):

Table 5-26: Engineering Cost Inputs

Option	Uncontrolled System (developing country)	Partially Controlled System (United States)	Partially Controlled System (Europe and Japan)	Source
Size of system (SF ₆ nameplate capacity)	100,000 pounds	100,000 pounds	100,000 pounds	N/A
Emission rate	16%	2.2%	0.5%	Expert judgment (uncontrolled systems); 2016 average rate from U.S. inventory (partially controlled system-US); Conservative estimate assumed per Glaubitz (2017) (partially controlled system-Europe/Japan)
Cost of bulk SF ₆ (per pound)	\$23.59	\$8.67	\$8.67	Rothlisberger (2018a) ^a
Labor cost of technician (per hour)	\$1.95	\$37.29	\$34.64	BLS, 2012
SF₆ Recycling				
Capital cost per gas cart	\$104,000	\$104,000	N/A	Expert judgment (middle of range provided by Rothlisberger [2011a])
Number of gas carts that could be used at 100,000-pound system	5	5	N/A	Expert judgment (middle of range provided by Rothlisberger [2011b])
Existing penetration of gas carts at facility	0%	85%	N/A	NCGC (2010) and National Electric Power Authority (NEPA) (2005) (uncontrolled systems); expert judgment (partially controlled systems)
Annual O&M labor per gas cart (hours)	780	780	N/A	Expert judgment (middle of range provided by Rothlisberger [2011b])

(continued)

Table 5-26: Engineering Cost Inputs (continued)

Option	Uncontrolled System (developing country)	Partially Controlled System (United States)	Partially Controlled System (Europe and Japan)	Source
Capital cost per gas cart	\$104,000	\$104,000	N/A	Expert judgment (middle of range provided by Rothlisberger [2011a])
LDAR (Thermal Imaging Camera)				
Capital cost per unit	\$107,000	\$107,000	N/A	Czerepuszko (2011a)
Number of cameras that could be used at 100,000-pound system	1	1	N/A	Czerepuszko (2011a)
Annual O&M labor per camera and associated repairs (hours)	400	200	N/A	Expert judgment
Existing penetration in region	3%	7%	N/A	Czerepuszko (2011a)
SF ₆ reduced through application (pounds)	827	284	N/A	N/A
LDAR (Handheld Leak Detector)				
Capital cost per unit	\$700	\$700	N/A	Ladzinski (2018)
Number of handheld detectors that could be used at 100,000-pound system	2	2	N/A	Expert judgment
Annual O&M labor per handheld detectors and associated repairs (hours)	400	200	N/A	Expert judgment
Existing penetration in region	50%	50%	N/A	Expert judgment
Technical applicability to baseline emissions	5%	5%	N/A	Rothlisberger (2011b) (uncontrolled systems); Rothlisberger (2011a) (partially controlled systems)
SF ₆ reduced through application (pounds)	3,309	284	N/A	N/A

(continued)

Table 5-26: Engineering Cost Inputs (continued)

Option	Uncontrolled System (developing country)	Partially Controlled System (United States)	Partially Controlled System (Europe and Japan)	Source
Equipment Replacement				
Capital cost per breaker	\$366,000	\$366,000	N/A	McNulty and Jasinski (2012)
Number of 145kV breakers (that would be subject to replacement) in a given year	8	8	N/A	Expert judgment (Using PG&E as an example facility and 230kV breakers as a proxy [Rak 2017b])
Percentage of leak-prone equipment already replaced	0%	10%	N/A	Expert judgment
Capital labor hours per replaced breaker	160	160	N/A	ICF Expert Judgement
SF ₆ reduced through application (pounds)	7,860	2,161	N/A	N/A
SF₆-Free Gas Insulated Equipment				
Capital cost per breaker	\$549,000	\$549,000	\$549,000	McNulty and Jasinski (2012) show the cost of breaker replacement ranges from \$200,000 for a 120kV breaker up to \$500,000 for a 345kV breaker. Ecofys (2018) reports that SF ₆ free MV (up to 36kv) GIE can be 30 to 50% more expensive than regular SF ₆ breakers (see Table 24 of Ecofys 2018)
Number of 145kV breakers (that would be subject to replacement) in a given year	8	8	8	Expert judgment (Using PG&E as an example facility and 230kV breakers as a proxy [Rak 2017b])
Percentage of leak-prone equipment already replaced	0%	0%	0%	Expert judgment

(continued)

Table 5-26: Engineering Cost Inputs (continued)

Option	Uncontrolled System (developing country)	Partially Controlled System (United States)	Partially Controlled System (Europe and Japan)	Source
Annual O&M labor hours per replacement	160	160	160	ICF Expert Judgement
SF ₆ reduced through application (pounds)	7,860	2,161	1,228	N/A
Improved SF₆ Handling				
Cost per adapter kit	\$1,500	\$1,500	N/A	Expert judgment (middle of range provided by Rothlisberger [2011a])
Number of adapter kits that could be used at 100,000-pound system	20	20	N/A	Expert judgment
Percentage of kits already purchased	50%	50%	N/A	Rothlisberger (2011a)
Number of technicians per system	23	23	N/A	Expert judgment (middle of range provided by Rothlisberger [2011b])
Number of annual training per technician (hours)	16	16	N/A	Rothlisberger (2011a)
Percentage of technicians already trained	50%	80%	N/A	Rothlisberger (2011a)
SF ₆ reduced through application (pounds)	59,570	8,191	N/A	N/A

^a Rothlisberger (2011a) provided a range of \$12 to \$20 USD for the estimated cost of bulk SF₆ in developing countries.

5.2.5.5 Sector-Level Trends and Considerations

Research into a gas or gas mixture to replace SF₆ for use in medium- and high-voltage equipment has been underway through pilot applications, primarily in Europe. SF₆-free alternative technology availability depends on the application in question. In medium-voltage equipment, established alternatives, such as vacuum technology, are commercially available; however, further research and development is needed to establish commercially viable, widespread adoption of SF₆-free alternatives for high-voltage equipment. That said, promising developments are underway. For example, National Grid, a utility in the United Kingdom, became the first utility to energize a SF₆-free 420 kV gas-insulated line in their Sellindge substation in April 2017. Additionally, in late 2017, the Etzel substation in Switzerland successfully tested the alternative Green Gas for Grid or g3, a fluoroketone-based mixture, on a 14- kV gas-insulated substation (T&D World, 2018). In the United States, utilities are beginning to take similar action to learn and plan for adoption of SF₆-free technology. In particular, in California, a state that

is currently proposing to phase out SF₆ gas, an insulating gas in transmission and distribution electrical equipment, several utilities are working together toward viable alternatives and a transition plan that can reduce costs, standardize replacement gases, and avoid duplication in their research and development (Rak, 2017a).

While additional efforts are necessary for a widespread transition to SF₆ alternatives in high-voltage switchgear, technology enhancements have optimized SF₆-insulated equipment over the past 30 to 40 years. As such, the amount of SF₆ 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 (Rhiemeier et al., 2010; Ecofys, 2018). The average age of SF₆-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 SF₆-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. The average SF₆-insulated circuit breaker in developing countries, therefore, was assumed to leak less than the average SF₆-insulated circuit breaker in developed countries.

Employee training and investments in SF₆ handling technologies (such as SF₆ recovery carts) vary widely among countries and regions. The use of equipment and accessories to properly handle SF₆ 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 SF₆ 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 EPA's voluntary SF₆ Emission Reduction Partnership for Electric Power Systems. Employee training is low to nonexistent in at least some developing countries (NEPA, 2005).

5.2.5.6 References

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5.2.6 Primary Aluminum Production

Emissions of the PFCs CF₄ and C₂F₆ are generated during brief process upset conditions in the aluminum smelting process. During the aluminum smelting process, when the alumina (Al₂O₃) 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 CF₄ and C₂F₆ emissions when carbon from the anode, instead of reacting with alumina as it does during normal operating conditions, combines with fluorine (F₂) 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.⁵¹

The most significant process emissions are:

- CO₂ emissions from the consumption of carbon anodes in the reaction to convert aluminum oxide to aluminum metal and
- PFC emissions of CF₄ and C₂F₆ during AEs (IPCC, 2006).

5.2.6.1 Primary Aluminum Production Emission Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full-time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for primary aluminum production included primary aluminum production data from United States Geological Survey (1995 through 2016) and historical global percentages of cell types derived from reports from the International Aluminium Institute (2016). Emission factors were obtained from IAI (2011), IPCC (2006), and Marks and Nunez (2018).

The Tier 1 basic equation (IPCC, 2006) used in this analysis to estimate PFC emissions from primary aluminum production is as follows:

$$\begin{aligned} E_{CF4} &= EF_{CF4,i} \bullet MP \\ \text{and} \\ E_{C2F6} &= EF_{C2F6,i} \bullet MP \end{aligned} \quad (5.14)$$

where:

- | | |
|--------------------|--|
| E_{CF4} | = Emissions of CF ₄ from aluminum production, kg CF ₄ |
| E_{C2F6} | = Emissions of C ₂ F ₆ from aluminum production, kg C ₂ F ₆ |
| EF _{CF4} | = Default emission factor by cell technology type i for kg CF ₄ /tonne aluminum |
| EF _{C2F6} | = Default emission factor by cell technology type i for kg C ₂ F ₆ /tonne aluminum |
| MP | = Metal production, tonnes aluminum |

Activity Data

Historical

The EPA estimated primary aluminum production for all aluminum-producing countries based on data from U.S. Geological Survey (USGS) Mineral Yearbooks for Aluminum (USGS, 1995 through 2016a; USGS, 2016b).

⁵¹ It should be noted that over the last several years there has been the discovery and documentation of nonanode effect (NAE)-related emissions. EPA 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.

Country-specific aluminum production was disaggregated to cell type using historical global percentages for 1990 through 2015 derived from the International Aluminium Institute's (IAI's) *Results of the 2010 Anode Effects Survey* (IAI, 2011) and *Results of the 2015 Anode Effects Survey* (IAI, 2016) reports.

Projected

Country-specific production projections from 2020 to 2030 were estimated based on aluminum production compounded annual growth rates (CAGRs) estimated from historical production data from 2005 through 2015 global production estimates (USGS, 2016a). To estimate production from 2030 to 2050, the CAGR was reduced by 50% based on expert judgment to account for slowing growth in global demand and slowing global population growth. Growth in aluminum production is dependent on fluctuations in the global economic situation (Dudin et al., 2017). The CAGRs used in this analysis reflect the expectation that aluminum production will continue to grow in the coming years as urbanization, industrialization, and economic development in BRIC and other emerging countries increase global demand (IAI, 2013b).

Country-specific aluminum production for 1990 through 2020 was disaggregated to cell type using historical global percentages (for 1990 through 2015) derived from IAI's *Results of the 2010 Anode Effects Survey* (IAI, 2011) and *Results of the 2015 Anode Effects Survey* (IAI, 2016) reports. Country-specific production projections from 2025 through 2050 were first disaggregated into "existing" or "new-build" production by comparing a country's production projection against that country's total production capacity in 2018 (Light Metal Age, 2018). Production less than or equal to a country's capacity in 2018 was considered existing production, and production greater than that amount was considered new-build production. Existing SWPB, HSS, and VSS facilities were assumed to be fully retired from 2015 to 2050, except in Russia where VSS facilities are expected to remain online (Marks, 2018). SWPB, HSS, and VSS production is linearly interpolated between 2015 and 2050. Existing production was disaggregated to cell type based on IAI production data (IAI, 2011 through 2016), and new-build production was assigned to the point-fed center work prebake (PFPB) (i.e., newer) cell type. Given the efficiency of this cell type, it was assumed that aluminum manufacturers will opt for this cell type for all new-build production (Marks, 2017).

Emission Factors

Historical and Projected

The EPA estimated PFC emission factors using the IPCC Tier 1 methodology (i.e., default emission factors multiplied by quantity of metal produced) (IPCC, 2006). Average cell type-specific emission factors for 1990 through 2010 are taken from IAI's annual Anode Effect Surveys (IAI, 2011). Emission factors for 2010 through 2015 were provided by Marks and Nunez (2018). Projected emission factors were assumed to be constant at 2015 levels through 2050 (Table 5-27).

Emission Reductions in Baseline Scenario

The base case analysis is intended to model the hypothetical scenario in which no further action is taken by the aluminum industry to reduce its emission rates below the 2015 levels. Although this scenario represents a break from the historical trend, future action by the aluminum sector is not guaranteed, and the rate of decline in emission intensities (metric ton CO₂e/metric ton aluminum) has decreased in recent years (i.e., since 2005).

Uncertainty

In developing these emission estimates, the EPA used multiple international datasets and the most recent IPCC guidance on estimating emissions from this source. Nevertheless, uncertainties exist in both the activity data and the emission rates used to generate these emission estimates.

Table 5-27: Baseline Emission Factors by Year (MtCO₂e/Mt Al)

Technology Type	1990	2000	2010	2020	2030	2040	2050
China							
PFPB	0.8	0.8	0.8	1.3	1.3	1.3	1.3
CWPB	2.9	1.8	0.6	1.3	1.3	1.3	1.3
SWPB	15.4	13.9	4.5	4.0	4.0	4.0	4.0
HSS	3.1	2.4	0.9	4.1	4.1	4.1	4.1
VSS	5.0	3.2	1.0	1.7	1.7	1.7	1.7
Rest of World							
PFPB	1.7	0.6	0.3	0.2	0.2	0.2	0.2
CWPB	3.5	1.8	0.6	0.2	0.2	0.2	0.2
SWPB	15.4	13.9	4.5	4.0	4.0	4.0	4.0
HSS	3.1	2.4	0.9	4.1	4.1	4.1	4.1
VSS	5.7	3.2	1.0	1.7	1.7	1.7	1.7

First, while this study incorporated recent data on total aluminum production by country from USGS Commodity Surveys and USGS Mineral Yearbooks, to disaggregate historical aluminum production by cell type, the EPA used information derived from IAI's *Results of the 2010 Anode Effects Survey* (IAI, 2011) and *Results of the 2015 Anode Effects Survey* (IAI, 2016) reports. This information provided the percentage breakout of total global production (which adjusts for nonreporters) by cell type for 1990 through 2015 used for the disaggregation. Therefore, these data may not be representative of the percentage breakout by cell type (and hence the emissions) for an individual country (or region). Cell type is important because emissions per ton of aluminum (i.e., effective emission factors) can vary by a factor of five or more across different cell types (IPCC, 2000). To disaggregate current (i.e., through 2025) and projected (i.e., post-2025) aluminum production by cell type, the EPA first disaggregated the data into existing or new-build production by comparing it with projected production in 2025; then for existing production, we adopted the percentage breakout of total global production estimated for 2025 for 2030 through 2050, with new-build production assigned as aluminum. Therefore, the resultant total production projection percentage breakout may not truly represent the future breakouts that would be derived from reported production data for the technology in place through 2050.

Second, the EPA used a single aluminum production compounded annual growth rate to project country-specific production through 2030, and a single growth rate to project country-specific production from 2030 to 2050. Future production in individual countries is likely to follow actual trends not reflected by an annual growth rate, and the value of an individual country's annual growth rate might be significantly different from that of the rest-of-world rate.

In addition, as previously discussed, the EPA assumed the emission factors estimated for 2015 when estimating emissions for 2020 through 2050. Therefore, these emission factors may not truly represent values that would be derived from reported data for the technology in place through 2050. Further, the methodology does not explicitly account for reductions from CDM projects, but the impacts of these projects are captured to some extent in the emission factors and cell type allocations taken from IAI.

It was assumed in this analysis that the vast majority of PFC emissions are generated during high-voltage AE events. However, recent research using more sensitive measurement equipment has shown that PFC emissions also occur during low-voltage AE events (Marks and Nunez, 2018), which are not accounted for in this analysis. Emission rates from low-voltage AEs are lower than rates from high-voltage AEs, but because emissions from low-

voltage effects can occur almost continuously, the associated emissions can be significant (Marks and Nunez, 2018). This analysis also does not account for additional PFC emissions associated with starting operations at a new facility (Marks, 2017).

The base case analysis assumes that no further action is taken by the aluminum industry to reduce their emission rates below the 2015 levels. However, the IAI notes that there has been an 88% reduction in global PFC emissions per metric ton since 1990 and a 35% reduction since 2006 (IAI, 2016). Although the rate of reduction in emission intensities has slowed in recent years, it is unlikely that actual emissions will be as high as those presented in the analysis.

5.2.6.2 Mitigation Options Considered for Primary Aluminum Production

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 PFPB.⁵² PFPB is considered the most technologically advanced process to produce aluminum, and all new greenfield smelters built in the world today use this technology. Existing, older, and higher PFC-emitting PFPB systems can further improve their AE performance by implementing management and work practices, as well as improved control software. Retrofits to CWPB cells were not analyzed in this analysis because they already operate at close to the same efficiency as PFPB cells in terms of emissions. Retrofits to CWPB cells are unlikely to occur given the economics and reductions would not be material (Marks 2018). Facilities using VSS, HSS, and SWPB 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. 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.⁵³

PFC emission reductions can primarily be achieved by installing/upgrading process computer control systems⁵⁴ and installing alumina point-feed systems.⁵⁵ 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.⁵⁶ The installation of alumina point-feed systems was 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.⁵⁷

⁵² It should be noted that PFPB and CWPB are essentially the same cell design but with different alumina feed processes.

⁵³ 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, U.K. http://www.world-aluminium.org/media/filer_public/2013/08/20/2012_anode_effect_survey_report.pdf.

⁵⁴ 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.

⁵⁵ Point-feed systems allow more precise alumina feeding.

⁵⁶ 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.

⁵⁷ 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.

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 cost analysis, a minor retrofit has a lifetime of 10 years for VSS, HSS, and SWPB facility types 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 represent the costs associated with purchasing and installing the process computer control systems at the aluminum production facilities. The capital costs for minor retrofit, obtained from International Energy Agency (IEA) (2000) and confirmed by Marks (2018), range from \$6.5 million to \$8.8 million (2016 USD), depending on the facility type. The annual O&M costs associated with minor 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). For minor retrofits, these costs range from approximately \$65,000 to \$130,000 (2016 USD), depending on the facility type.

It was assumed that model facilities would use the increased current efficiency (aluminum production/unit of electricity) resulting from the retrofits 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).⁵⁸ Increased current efficiencies for each facility and retrofit are available from IEA (2000). The additional revenues associated with the minor retrofit option, depending on the facility type range between \$0.5 million to \$1 million (2016 USD).

Major Retrofit

A major retrofit involves both the installation/upgrade of process computer control systems and the installation of alumina point-feed systems. Major retrofits result 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 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 AE performance as point feeders. By definition, a PFPB model facility has point-feeding systems, so there is no opportunity for additional application.

The capital costs for major retrofits 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 for major retrofits, obtained from IEA (2000) and confirmed by Marks (2018), range from \$13 million to \$98 million (2016 USD), depending on facility type. Additionally, annual O&M costs range from \$390,000 to \$3.7 million (2016 USD), depending on facility type. Annual revenues for major retrofits range from \$1 million to \$2 million (2016 USD), depending on facility type. The expected lifetimes for major retrofits was assumed to be 10 years.

5.2.6.3 Model Facilities

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

⁵⁸ 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.

$\text{CO}_2\text{e}/\text{metric ton aluminum}$)—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 5-28 presents a description of the model facilities considered for this analysis.

Table 5-28: Description of Primary Aluminum Production Facilities

Facility Type	Description
VSS	This facility uses VSS technology with an average PFC emission factor of 1.21 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. 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 1.39 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. 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 3.49 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. 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 0.18 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. 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 0.20 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. The production capacity of the facility is 200,000 metric tons per year. ^a

^a It should be noted that the “state of the art” has been improving rapidly with respect to AE performance, and the best PFPB facilities (top 10%) are performing at better than 0.06 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$. Median performance for all IAI non-Chinese producers is about 0.23 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$, while median Chinese PFPB performance is about 0.8 metric tons $\text{CO}_2\text{e}/\text{metric ton aluminum}$ (IAI 2017).

5.2.6.4 Technical and Economic Characteristics Summary

Technical effectiveness is the parameter used to assess the abatement potential from each technology option. The technical effectiveness parameter determines the share of emission 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 emission reductions achievable by each technology/facility combination. Estimating this parameter required assumptions regarding the distribution of emissions by manufacturing process (i.e., VSS, HSS, SWPB, 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 5-29 presents the market penetration, 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.

Table 5-29: Technical Effectiveness Summary—Primary Aluminum Production

Abatement Option	Model Facility Type	Technical Applicability	Market Penetration	Reduction Efficiency	Technical Effectiveness
Minor retrofit					
	VSS	100%	50%	39%	11%
	HSS	100%	50%	39%	20%
	SWPB	100%	50%	24%	12%
	PFPB	100%	100%	55%	55%
Major retrofit					
	VSS	73%	50%	77%	56%
	HSS	100%	50%	78%	39%
	SWPB	100%	50%	96%	48%

The technical applicability factor for VSS assumes that roughly 27% of VSS capacity already has point feeding (Marks, 2011). Table 5-30 documents the facility-level engineering cost data used in the MAC analysis for the primary aluminum production sector.

Table 5-30: Engineering Cost Data on a Facility Basis—Primary Aluminum Production

Abatement Option	Facility Type	Project Lifetime (years)	Capital Cost (2016 USD)	Annual Revenue (2016 USD)	Annual O&M Costs (2016 USD)	Abatement Amount (tCO ₂ e)
Minor retrofit	VSS	10	\$6,582,874	\$1,052,475	\$131,657	103,000
	HSS	10	\$6,582,874	\$526,237	\$65,829	121,000
	SWPB	10	\$6,866,347	\$789,356	\$102,995	165,500
	PFPB	30	\$8,834,909	\$526,237	\$88,349	4,000
Major retrofit	VSS	10	\$93,057,897	\$2,104,949	\$3,722,316	206,000
	HSS	10	\$98,002,926	\$1,052,475	\$1,960,059	242,000
	SWPB	10	\$12,992,514	\$1,578,712	\$389,775	662,000

5.2.6.5 Sector-Level Trends/Considerations

The emission projections (i.e., baseline emissions) account for the historical reduction in the effective emission factor (i.e., metric ton CO₂e/metric ton aluminum) 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 with 2006 (IAI, 2013a). In addition, commissioning of new, less emissive facilities to meet global demand will also have the result of reducing the effective emission factor.

This analysis does not consider “breakthrough” technologies, which, if developed and widely implemented, could significantly reduce GHG emissions from aluminum production. One potential breakthrough technology is the use of inert anodes. An inert anode is chemically nonreactive and so does not react to the electrolysis process and is not consumed during production. Due to the high corrosiveness of the cryolitic melts, it is difficult to

develop an anode that is truly inert or even slowly consumable. Alcoa announced in 2000 that it was working with inert anodes but had not proved the commercial feasibility (Kvande and Drabløs 2014). In May of 2018, Apple announced that it has partnered with Alcoa and Rio Tinto to commercialize the technology, and along with the governments of Canada and Quebec, invest a combined \$144 million in research and development. Sufficient economic data was not available to include this technology as part of this analysis (Apple 2018).

5.2.6.6 References

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5.2.7 Magnesium Production

The magnesium metal production and casting industry uses SF₆ as a cover gas to prevent the spontaneous combustion of molten magnesium in the presence of air. Fugitive SF₆ emissions occur primarily during three magnesium manufacturing processes: primary production, die casting, and recycling-based production. Additional processes that may use SF₆ include sand and gravity casting, as well as wrought, anode, and permanent mold casting; however, these are not included in this analysis.

5.2.7.1 Magnesium Production Emission Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for magnesium manufacturing included primary magnesium production data from USGS (2007, 2009, and 2017), die-casting production data from Harnisch and Schwarz (2003) and Edgar (2004), automobile production from Ward's Motor Vehicle Data (2001) and the International Organization of Motor Vehicle Manufacturers (2017), and production growth rates from Webb (2005). Emission factors were obtained from Gjestland and Magers (1996) and EPA (2010). Emission reductions were incorporated based on the EPA's SF₆ Emission Reduction Partnership for the Magnesium Industry, facility-reporting to the EPA Greenhouse Gas Reporting Program (GHGRP), regulations phasing-out and banning SF₆ in the European Union, and several magnesium CDM projects.

The 2006 IPCC Tier 1 methodology (IPCC, 2006) was used to estimate emissions from magnesium manufacturing as follows:

$$E_{SF_6} = MG_c * EF_{SF_6} * 10^{-3} \quad (5.15)$$

where:

E_{SF_6} = SF₆ emissions from magnesium casting, tonnes

MG_c = Total amount of magnesium casting or handling in the country, tonnes

EF_{SF_6} = Default emission factor for SF₆ emissions from magnesium casting, kg SF₆/tonnes Mg casting

In the absence of emission control measures, the rapid growth of the magnesium manufacturing industry is expected to significantly increase future SF₆ emissions from magnesium production and processing. However, efforts in recent years to eliminate the use of SF₆ in this application around the world have reduced potential emission growth. In 2003, the EPA's SF₆ Emission Reduction Partnership for the Magnesium Industry formed a global industry commitment through the International Magnesium Association (IMA), which represents approximately 80% of magnesium production and processing outside of China, to eliminate SF₆ emissions from magnesium operations by the end of 2010. The U.S. partnership has ended, but facilities in the United States that contain magnesium production processes are required to annually report emissions under subpart T of EPA's Greenhouse Gas Reporting Program (GHGRP) (40 CFR Part 98). In addition, regulatory efforts in Europe and Japan and CDM projects in Brazil and South Korea have resulted in reduced emissions. So far, two magnesium projects have been registered with CDM: 1 project from Israel and 1 from Brazil (CDM Project Activities, 2018).

Activity Data

Historical

Activity data for the three different magnesium manufacturing types are discussed below.

Primary Production

Primary magnesium production data for 1990 through 2015 were obtained from the USGS (2007, 2009, 2017).

Die-Casting Production

Die-casting production activity data were obtained from various sources as outlined below.

- *EU.* For Portugal, Spain, and the U.K., historical SF₆ emissions were estimated using country-specific data on SF₆-based magnesium casting production from Harnisch and Schwarz (2003). For 1990, emissions were estimated using the 1995 estimates and two trends between 1990 and 1995: (1) EU auto production and (2) magnesium used per car in the United States between 1990 and 1995. Based on these trends, SF₆ emissions in the EU from die-casting production that were based on car production were assumed to have increased by 30% between 1990 and 2015, and emission factors were assumed to remain constant over the same period.
- *China (2000, 2005, and 2010 only).* The activity data used for Chinese historical SF₆ emissions from magnesium manufacturing was Chinese casting volume for the years 2000, 2005, and 2010 from Edgar (2004). For the intervening years, die-casting production was estimated using the ratio of country-specific automobile production to U.S. automobile production. This ratio was multiplied by U.S. die-casting production to obtain an estimate of die-casting production in each country. Automobile production for 1990 to 2000 was obtained from Ward's Motor Vehicle Data (Ward's, 2001), and 2001 through 2015 production data were obtained from the International Organization of Motor Vehicle Manufacturers (2017).
- *Other countries.* For other countries, die-casting production for the years 1990 through 2012 was estimated as a function of automobile production. For example, for Brazil, Russia, and Ukraine, die-casting production was estimated using the same methodology for estimating die-casting production in China for years other than 2000, 2005, and 2010. For countries that did not produce automobiles but had growing die-casting industries, such as Kazakhstan and Israel (IMA, 2002), production was estimated from the ratio of primary production to die-casting production for a similar country. Russia was used as a proxy for estimating production in Kazakhstan, while the United States was used as a proxy for Israel. Taiwan was assumed to acquire 12.5% of Japan's die-casting activity starting in 2002, increasing linearly to 50% by 2005.

Recycling-Based Production

Recycling-based production for Brazil, China, Russia, the U.K., and countries in the EU was estimated using die-casting activity and a “remelt factor” of 30%. The secondary production to die-casting ratio ranges from 30% to 55% across countries that actively recycle scrap magnesium (Edgar, 2006), and 30% was chosen as a conservative default for those countries where emissions were calculated for this source. The Czech Republic was reported to have a new recycling plant come online in 2002 and was assumed to have an annual growth rate of 3.4% through 2010 and then 1.7% from 2011 through 2015 (Webb, 2005). Table 5-31 presents the growth rates used in this analysis.

Projected

Annual growth rates for primary casting and recycling production are summarized in Table 5-31. In general, annual growth rates used in this analysis were assumed to account for new facility construction and facility capacity expansion, driven by growing global demand for magnesium in applications such as automotive lightweighting to improve fuel economy. Primary production and die-casting production growth rates were based on information supplied by Webb (2005) for the rest of the countries’ estimates. Recycling production was estimated based on the growth rates associated with die-casting production.

Table 5-31: Annual Growth Rates for Primary Production, Casting, and Recycling Production (annual percentage increase)

Years	Primary Production Annual Growth Rates ^a (%)			Casting Annual Growth Rates (%)				Recycling Annual Growth Rates ^a (%)
	China	Rest of World	Rest of World	Asia	China	Europe	Russia	World
2016–2035	5.5 ^b	1.7	1.7	4.8	5.0	1.7	4.8	Same as casting ^c
2036–2050	0.0 ^c	0.8	0.8	2.4	2.5	0.8	2.4	Same as casting ^c

^aSource: Primary and casting growth rates were based on Webb (2005). For recycling, it was assumed that growth rates will be driven by increasing use in automotive applications; consequently, growth rates will be the same as casting estimates.

^bAnnual growth for China was estimated to be 5.5% through 2020 and then held at zero for 2020 through 2050.

^cFor EU countries, this growth rate was applied until 2015 when the EU regulation to phase out the use of SF₆ in recycling came into effect

Primary Production

Primary production was assumed to grow 1.7% per year between 2016 and 2035. Between 2036 and 2050, growth was assumed to decrease to an annual rate of 0.8%. Primary production in China is projected to grow at a rate of 5.4% from 2016 through 2030, to be consistent with 2010 through 2015 historical growth (USGS, 2017) and then projected to hold steady at 2030 levels through 2050. For South Korea, primary production was projected to grow at 3.4% per year from 2016 through 2035 and 1.7% per year from 2036 through 2050. This is consistent with Roskill (2016), which estimates that by 2020 the global production growth rate of magnesium metal will average 3.4% per year and the die-casting growth rate will be 4.0%.

Die-Casting Production

In Asia (except China) and Russia, die-casting production is expected to grow at 4.8% per year from 2016 through 2035 (Webb, 2005) and at 2.4% annually between 2036 and 2050. For Europe and other countries such as Brazil, Israel, Kazakhstan, and Ukraine, die-casting production is estimated to grow at 1.7% annually from 2016 through 2035, and 0.8% annually from 2036 through 2050. From 2016 through 2035, die-casting production in China is estimated to grow at 5.5% annually. This growth is spurred by increasing investments by western, Japanese, and Taiwanese companies in China to meet domestic demand for camera, computers, and automobile parts. Die-casting production between 2036 and 2050 for China was assumed to hold constant.

Recycling-Based Production

For all countries with projected emission estimates, recycling growth rates were set equal to die-casting growth rates.

Emission Factors

Historical and Projected

SF₆ emissions were conservatively assumed to be equivalent to SF₆ consumption (i.e., it was assumed that no SF₆ is destroyed during the metal processes). Table 5-32 and Table 5-33 summarize the emission factors used to estimate historical emissions for each of the production processes for all countries in this analysis. The emission factor for primary production was based on measurements made in 1994 and 1995 by U.S. producers. Because of the similarity between the primary and recycling production processes, the emission factor for recycling production was assumed to be the same as the emission factor for primary production. The emission factor for die casting was obtained from a 1996 international survey of die casters performed by Gjestland and Magers (1996). It was assumed that the 2010 emission factors obtained from the EPA's SF₆ Emission Reduction Partnership for the

Table 5-32: Emission Factors for Primary Production, Casting, and Recycling Production (1990–1999)

Process	Emission Factors (kg SF ₆ /metric ton Mg produced) ^a	Source
Primary production	1.10	EPA, 2010
Casting	4.10	Gjestland and Magers, 1996
Recycling	1.10	EPA, 2010

^aEmission factors used to estimate emissions from Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and the U.K., as appropriate.

Table 5-33: Emission Factors for Primary Production, Casting, and Recycling Production (2000–2050)

Process	Emission Factors (kg SF ₆ /metric ton Mg produced) ^a	Source
Primary production	0.75	EPA, 2010
Casting	1.00	EPA, 2010
Recycling	0.75	EPA, 2010

^aEmission factors used to estimate emissions from Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and the U.K., as appropriate.

Magnesium Industry remain constant from 2011 through 2050. The 2000 emission factor for primary production was based on measurements made by four producers (i.e., producers with U.S. and international operations) (EPA, 2010) and was held constant from 2010 through 2050. For all countries including China, the emission factors for die casting were estimated based on reports from U.S. die casters and a report on emissions from European die casters (Harnisch and Schwarz, 2003).

Emission Reductions in Baseline Scenario

Emission reductions that are applicable for the base case scenario include the following:

- In the United States, reductions that occurred as a result of the voluntary partnership are reflected in the estimates. Additionally, some facilities have reported to EPA's GHGRP program that they use HFC-134a for magnesium production and processing. Reductions in SF₆ emissions due to HFC-134a emissions in the United States were accounted for in the UNFCCC-reported emission data.
- In the EU, a 2006 regulation, as defined in Article 13 of the EU F-GHG Regulation No. 517/2014 (Office Journal of the European Union, 2014), banned the use of SF₆ in magnesium die casting for plants using more than 850 kg per year. Starting in 2008, all EU die-casting facilities that use more than 850 kg of SF₆ per year were required to stop using SF₆. SF₆ emissions from smaller facilities (those using less than 850 kg in die casting), which was assumed to be the average proportion of die-casting emissions reported to the EPA GHGRP relative to total die-casting emissions (i.e., 41%), were assumed to linearly phase out between 2008 and 2018.
- In 2014, the EU regulation phasing out SF₆ emissions from die casting was extended to SF₆ emissions from recycling. Starting in 2015, all EU recycling facilities that use more than 850 kg of SF₆ per year were required to stop using SF₆. For recycling facilities smaller than this threshold, emissions were assumed negligible.
- In 2018, SF₆ is banned from use in the EU for any magnesium die-casting and recycling process, regardless of facility size. Therefore, emissions were zeroed out for EU countries from 2018 through 2050.

- Magnesium recyclers in the U.K. have switched to sulfur dioxide (SO_2) since 2000; therefore, the U.K.'s SF_6 emissions from magnesium recycling from 2000 through 2050 were assumed to be zero.
- Emission reductions from several magnesium CDM projects, including those in Brazil and Israel, are reflected in the base case. RIMA, a large-scale magnesium production and processing facility in Brazil, implemented a full conversion to SO_2 for its primary, die-casting, and recycling activities and is monitoring with CDM through 2023 (UNFCCC, 2018). Dead Sea Magnesium and Ortal Diecasting 1993 Ltd. in Israel implemented a conversion from primary production to HFC-134a and is implementing the SF_6 abatement action plan, with financial support from CDM, through 2019 (UNFCCC, 2010; UNFCCC, 2017). The Brazil and Israel CDM project reports provided SF_6 emission reductions for primary and die-casting production processes. From the last year of CDM available data (i.e., 2016 for Brazil and 2012 for Israel) through 2050, emission reductions were assumed to remain constant and continue from CDM project implementation. Emission reductions were assumed to be held constant in absolute terms from the latest CDM monitoring reports (i.e., from 2016 for Brazil and from 2012 for Israel). The EPA assumed that the technology implemented to achieve SF_6 emission reductions remains in use by the facilities after the end of the CDM project.

Uncertainties

Historical and projected emissions from this source are affected by both activity levels and emission rates. Although country-specific activity levels are fairly well known for primary production, they are less well known for recycling-based production, particularly the share consisting of magnesium-base alloys and the share for die casting. In addition, emission rates vary widely across different processes and over time. The EPA accounted for these variations (e.g., the decline in emission rates that occurred between 1995 and 2000), but some regional- and process-based variability may exist.

In addition, projected emissions from magnesium production and processing are sensitive to estimated activity growth rates and to assumptions regarding the adoption and/or retention of alternative melt protection technologies. The EPA used relatively high activity growth rates to project emissions; therefore, slight changes in these rates would lead to large changes in projected emissions. Furthermore, population growth and economic development resulting from purchasing power growth will likely affect magnesium consumption on a per capita basis, and therefore total emissions from magnesium production processes. This analysis does not include projections based on the effects of such growth.

This analysis also assumed that some, but not all, of Chinese magnesium producers have adopted SF_6 in place of solid sulfur powder as these producers seek to increase metal quality. Because China is currently the world's largest producer of magnesium, greater penetration of the Chinese market by SF_6 would significantly increase both Chinese and global emissions. On the other hand, penetration of the Chinese die-casting market by alternative cover gases would lower Chinese emissions below those projected in this analysis.

Finally, the assumption that SF_6 emissions are equivalent to SF_6 consumption may overstate emissions, because recent EPA studies have shown that 5% to 20% of the SF_6 degrades during its use as a cover gas during at least one type of casting process (Bartos et al., 2003).

5.2.7.2 Mitigation Options Considered for Magnesium Production

Use of SF_6 as a cover gas is the only source of GHG 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 IPCC guidelines (2006), which assumes that all SF_6 used is emitted to the atmosphere.

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 is not common or was discontinued in most countries.

Historic and recent SO₂ technology research aims to improve process feed systems and control technology and to address the toxicity and odor issues with improved containment and pollution control systems (Environment Canada, 1998), nonetheless this option is still not very common in most countries. The use of SO₂ has the potential to reduce SF₆ emissions by 100% because a complete replacement of the cover gas system is involved. Currently, SO₂ is being used as a cover gas; for example, it is used as a cover gas at one die-casting facility in Brazil (UNFCCC, 2010b). This option was assumed to be technically applicable to all three model facilities. The maximum market penetration for this option was assumed to be 80% of the emissions of SF₆ for recycle/remelt facilities and 10% for both die-casting and primary production facilities. The lifetime of this option was assumed to be 15 years.

Facilities implementing SO₂ 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 \$522,070 for all three facility types. Facilities also incur annual costs (or generate annual cost savings) based on the purchase price of the alternative cover gas. This option results in annual gas purchase costs of \$5,953 each for die-casting and primary production facilities and an annual gas purchase cost of \$26,591 for recycle/remelt facilities. SO₂ is significantly less expensive than SF₆, and the required gas replacement ratio is 1:1, resulting in a significant net savings in material costs. Replacing SF₆ with SO₂ also results in avoided costs of \$36,910 each for both die-casting and primary production model facilities and \$588,018 for the recycle/remelt model facility associated with the purchase of SF₆.

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 SF₆ (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). In addition, currently, HFC-134a is used as a cover gas at two die-casting facilities in Israel (UNFCCC, 2008a, 2008b) and at least four facilities in the United States (EPA, 2018). While F-GHGs have an advantage over SO₂ because they have potentially fewer associated health, safety, odor, and corrosive impacts, some current F-GHG alternatives (including HFC-134a) still have climate impacts, albeit relatively minimal. The GWP of HFC-134a is significantly less than that of SF₆; thus, the GWP-weighted cover gas emissions could be reduced by 94%. HFC-134a was assumed to be technically applicable to all model facilities. The maximum market penetration for this option was assumed to be 45% of the emissions of SF₆ for die-casting and primary production facilities and 10% for recycle/remelt facilities. The lifetime of this option was assumed to be 15 years.

Facilities implementing HFC-134a as an alternative cover gas do not incur upfront 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 \$49,055 each for die-casting and primary production facilities and \$219,135 for the recycle/remelt facility. HFC-134a is not only less expensive than SF₆, but additionally HFC-134a has a gas replacement ratio of 0.71:1, resulting in significant net savings in material costs. Replacing SF₆ with HFC-134a results in avoided costs of \$36,910 each for both die-casting and primary production model facilities and \$164,880 for the recycle/remelt facility associated with the purchase of SF₆.

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 SF₆ (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). Additionally, currently, Novec 612 is being used at one die-casting facility and one remelt facility in the United States (EPA, 2018). The use of Novec 612 as an alternative cover gas represents an advantage over SO₂ because, like other F-GHGs, 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 SF₆. Novec 612 was assumed to be technically applicable to all model facilities.

Facilities implementing Novec 612 as an alternative cover gas incur capital costs related to purchasing computerized mass flow control cabinets and piping material to direct the gas. The total capital cost was \$270,092.85 for the die-casting facility, \$36,462.59 for the recycle/remelt facility, and \$528,595.94 for the primary production facility. Use of Novec 612 results in annual gas purchase costs of \$114,799.27 for die-casting and primary production facilities and \$512,819.56 for the recycle/remelt facility. However, because the replacement ratio of Novec 612 to SF₆ 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 SF₆, an annual cost savings of \$36,910 for both die-casting and primary production model facilities and \$164,880 for the recycle/remelt model facility.

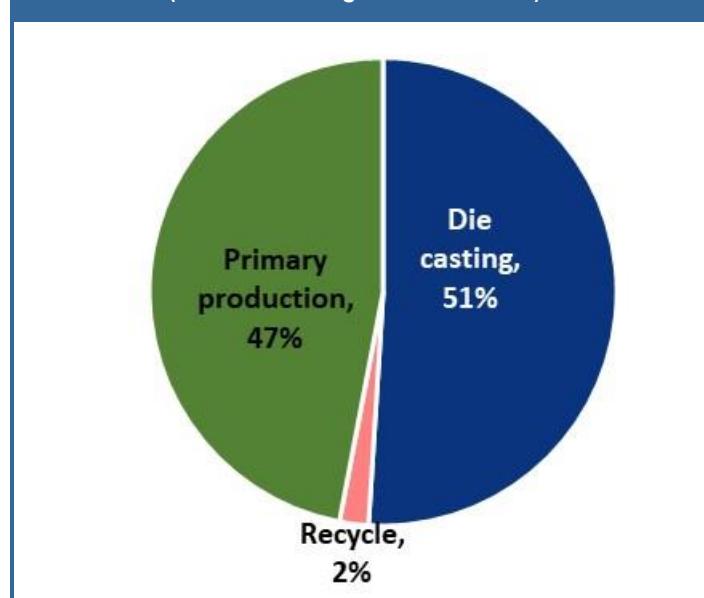
5.2.7.3 Model Facilities

To evaluate the cost of reducing SF₆ emissions from magnesium production, this analysis considered reduction costs for three typical magnesium production facilities, which were generally characterized based on facility-specific case studies measuring average SF₆ consumption, production capacity, and type. Global SF₆ emissions from magnesium production by facility type are shown in Figure 5-3. Model facilities are based on industry data from the United States but apply to magnesium facilities globally.

We characterize these typical facilities as follows:

- **Die-Casting Facility:** This model facility represents a medium-sized die-casting facility. The facility was characterized based on real data from a case study (EPA, 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 SF₆ per metric ton of magnesium produced, representing a total annual facility emission of 4,483 kg of SF₆. Production and emission data from 2007 were used to define the pre-abatement emission baseline (EPA, 2011).⁵⁹
- **Recycle/Remelt Facility:** This model facility represents a medium-sized recycle facility. The facility was 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 SF₆ per metric ton of magnesium produced, representing a total annual facility emission of 20,026 kg of SF₆. Production and emission data from the prior year (i.e., 2007) were used to define the pre-abatement emission baseline (EPA, 2011).
- **Primary Production Facility:** This facility assumes the same characteristics as the die-casting facility.

Figure 5-3: Global SF₆ Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



⁵⁹ We relied on data from the EPA case study as it is reliable and complete. Data from EPA's GHGRP contains confidential business activity data that was not accessible for this study.

5.2.7.4 Technical and Economic Characteristics Summary

Three potential options are available for reducing SF₆ emissions from magnesium production and processing operations. These emission abatement measures all include replacing SF₆ with an alternative cover gas: SO₂, HFC-134a, or Novec 612. Table 5-34 presents the reduction efficiency and applicability for the three alternative cover gas options.

Table 5-34: Magnesium Production Abatement Options

Abatement Option	Reduction Efficiency, %	Applicability
Alternative cover gas—Novec 612	100%	<ul style="list-style-type: none"> • Die casting • Recycle/remelt • Primary production
Alternative cover gas—HFC-134a	95%	<ul style="list-style-type: none"> • Die casting • Recycle/remelt • Primary production
Alternative cover gas—SO ₂	100%	<ul style="list-style-type: none"> • Die casting • Recycle/remelt • Primary production

Table 5-35 presents the costs and other assumptions associated with the options analyzed. All options have an assumed lifetime of 15 years.

Table 5-35: Engineering Cost Data on a Facility Basis—Magnesium Production

Abatement Option	Facility Type	Project Lifetime (years)	2016 USD Costs, \$			Abatement Amount (tCO ₂ e)
			Capital	Annual Savings ^a	Annual O&M	
SO ₂	Die casting	15	522,070	36,910	5,953	102,212
	Recycle/remelt	15	522,070	164,880	26,591	456,593
	Primary production	15	522,070	36,910	5,953	102,212
HFC-134a	Die casting	15	—	36,910	49,055	97,661
	Recycle/remelt	15	—	164,880	219,135	436,260
	Primary production	15	—	36,910	49,055	97,661
Novec 612	Die casting	15	270,093	36,910	114,799	102,210
	Recycle/remelt	15	36,463	164,880	512,820	456,582
	Primary production	15	5428,596	36,910	114,799	102,210

^a These numbers are not net annual savings.

5.2.7.5 References

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5.2.8 Use of Substitutes for Ozone-Depleting Substances

This section covers projections and mitigation options for the following source categories:

- HFC emissions from refrigeration and ACs
- HFC emissions from solvent use
- HFC emissions from foams manufacturing
- HFC emissions from aerosol product use
- HFC and PFC emissions from fire protection

5.2.8.1 Use of Substitutes for Ozone-Depleting Substances Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. If country-reported emission estimates were not available for any historical years, the EPA used a modeling approach to determine emissions from the various ODS substitute end-use sectors (refrigeration/AC, foams, aerosols, fire extinguishing, and solvents). EPA modeled emissions based on country-reported ODS consumption data to United Nations Environment Programme (UNEP) (2018). Allocation of emissions to each end-use sector in the United States was modeled using the Vintaging Model from EPA (2017). Emissions by end-use sector from non-U.S. countries were estimated by building on the U.S. assessment; then country-specific adjustments were made using factors for economic growth, timing of the ODS phase-out, types of alternatives employed, distribution of ODSs across end-uses in each region or country, and country-specific HFC consumption from the Multilateral Fund (MLF) from UNEP (2017a). The model incorporated measures to reduce or eliminate future emissions of these gases based on regulations by the United States, European Union, Australia, Canada, and Japan. Specific deviations from this basic methodology were made for several sectors and are discussed in the sections that follow. This methodology is described in more detail in the following sections.

Activity Data

The EPA used the Vintaging Model of ODS- and ODS-substitute-containing equipment and products to estimate the use and emissions of ODS substitutes in the United States. The model tracks the use and emissions of each of the substances separately for each of the ages or “vintages” of equipment. The Vintaging Model is used to produce the ODS substitute emission estimates in the official U.S. GHG Inventory and is updated and enhanced annually. For this analysis, the Vintaging Model was adapted slightly to include data sources common to each source category (e.g., GDP).⁶⁰

After U.S. emissions were calculated using the Vintaging Model, the EPA developed emission estimates for non-U.S. countries by building on the detailed U.S. assessment. In developing these estimates, the EPA initially assumed that the transition from ODSs to HFCs follows the same substitution patterns as the United States. The U.S.-based substitution scenarios were then customized to each region or country using adjustment factors that take into consideration differences in historical and projected economic growth, the timing of the ODS phase-out, the type of alternatives employed, and the distribution of ODSs across end uses in each region or country. The general methodology and assumptions used by the EPA are discussed below, although the methodology was modified for several sectors when necessary. Specific deviations from this basic methodology are discussed following the general methodology description.

The consumption of ODS and ODS substitutes was modeled by estimating the quantity of equipment or products sold, serviced, and retired each year and the amount of the chemical required to manufacture and/or maintain the equipment over time. The model estimates emissions by applying an emission profile (e.g., annual leak rates, service emission rates, and disposal emission rates for AC and refrigeration end uses) to each

⁶⁰ A discussion of the Vintaging Model can be found in the U.S. Inventory of Greenhouse Gas Emissions and Sinks (EPA, 2017).

population of equipment. The model estimates and projects annual use and emissions of each compound over time by aggregating the consumption and emission output from approximately 65 different end uses.

The major end-use sectors defined in the Vintaging Model for characterizing ODS use in the United States are refrigeration and AC, aerosols (including metered-dose inhalers [MDIs]), solvent cleaning, fire extinguishing equipment, foam production, and sterilization. The Vintaging Model estimates the use and emissions of ODS substitutes by taking the following steps:

1. *Gather historical emission data.* The Vintaging Model is populated with information on each end use, taken from published and confidential sources and industry experts.
2. *Simulate the implementation of new, non-ODS technologies.* The Vintaging Model uses detailed characterizations of the historical and current uses of the ODSs, as well as data on how the substitutes are replacing the ODSs, to simulate the implementation of new technologies that ensure compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end uses over time as seen historically and as projected for the future considering the need to comply with the ODS phase-out.
3. *Estimate emissions of the ODS substitutes.* The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions were estimated from the emission profile for each vintage of equipment or product in each end use. By aggregating the emissions from each vintage, a time profile of emissions from each end use is developed.

Historical

The following general steps were applied to estimate country-specific emissions. Steps 1 through 7 result in preliminary emission estimates calculated by Equation 5.16 below. The preliminary consumption estimates were adjusted to emissions and based on a regional or economic factor as discussed in Steps 8 through 11.

1. *Gather base ODS consumption data for each country.* UNEP (2010) provided reported ODS consumption in terms of ozone depletion potential (ODP)-weighted totals for the major types of ODSs: CFCs, HCFCs, halons, carbon tetrachloride, and methyl chloroform. The base year for estimates was 1989 because, in general, ODS substitution had not yet taken place; when data for 1989 were unavailable, the earliest available data were used as a proxy. Because data were only available in ODP-weighted totals by ODS “group,” groups were divided into component chemicals (e.g., CFC-11, CFC-12) according to 1990 U.S. percentages as modeled in the Vintaging Model. After disaggregating the ODP-weighted consumption by chemical, ODPs were used to determine the total consumption in metric tons.
2. *Calculate the percentage of base ODS consumption of each chemical group used in each end-use sector.* The amount of ODSs used in various industrial sectors differs by country. Data on the end-use distributions of ODS in 1990 were available for the following countries:
 - United States from the Vintaging Model
 - UK from *U.K. Use and Emissions of Selected Halocarbons*, prepared for the Department of the Environment (March 1996)
 - Russia from *Phaseout of Ozone Depleting Substances in Russia*, prepared for the Ministry for Protection of the Environment and Natural Resources of The Russian Federation and the Danish Environmental Protection Agency (Russian Federation, 1994)

The 1990 end-use sector distribution for the United States was applied to Canada and Japan. The UK’s distribution was applied to the EU-15,⁶¹ non-EU Western Europe,⁶² Australia, and New Zealand. Russia’s distribution was applied to the FSU and Eastern European countries. For developing countries, data on the 1990

⁶¹ For the purposes of this report, the U.K. is considered part of the EU. Hence, the EU-15 is defined as these EU members: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the UK.

⁶² Iceland, Liechtenstein, Monaco, Montenegro, Norway, and Switzerland.

consumption of ODS were available for many nations⁶³ by sector and substance from the Multilateral Secretariat. For developing countries that did not have data available, the EPA used a representative average of the published data (Rest of World).

3. *Calculate the base consumption of ODSs for each end-use sector.* This step involves multiplying the amount of consumption of each chemical group from Step 1 by the end-use sector distribution percentages from Step 2.
4. *Obtain conversion ratios.* Ratios of HFC consumption to base ODS consumption and HFC emissions to base HFC consumption were obtained from the Vintaging Model for each given year, chemical, and end use. These ratios are used to convert ODS consumption to HFC emissions.
6. *Estimate HFC consumption in metric tons.* This step involves multiplying the country-specific base level consumption of ODSs (Step 3) by the ratio of HFC consumption to base-level ODS consumption (Step 4).
6. *Estimate HFC emissions in metric tons.* This step requires multiplying the HFC consumption (Step 5) by the ratio of HFC emissions to HFC consumption (Step 4).
7. *Estimate GWP-weighted ODS substitute emissions in metric tons of CO₂ equivalent.* This step involves multiplying HFC emissions (Step 6) by an average GWP to derive GWP-weighted HFC emissions. The average GWP, which varies by sector, is determined by examining the estimated ODS substitute emissions in 2015 in the United States, as obtained from the Vintaging Model. The year 2015 was used as a representative average; the U.S. HFC market was assumed to be mature by this date and, under a BAU scenario, the mix of HFCs and other ODS substitutes (and hence the average GWP) is not expected to change significantly thereafter. For instance, this year is beyond the recent (January 1, 2010) U.S. and Montreal Protocol HCFC phaseout step. Regional policies that are expected to change the mix of HFCs (and hence average GWP), such as the EU F-GHG Regulation, are incorporated in a later step.

Equation 5.16: Preliminary Estimate Emissions Calculations

<i>HFC Emissions</i>	<i>ODS Consumption</i>	<i>HFC Consumption (MT) [U.S., year]</i>	<i>HFC Emissions (MT) [U.S., year]</i>	<i>Average GWP of HFC Emissions</i>
<i>(MtCO₂e) [country, year]</i>	<i>(MT) [country, 1989 or as available]</i>	<i>X</i>	<i>X</i>	
		<i>ODS Consumption (MT) [U.S., 1989]</i>	<i>HFC Consumption (MT) [U.S., year]</i>	
		<i>Step 3</i>	<i>Step 5</i>	<i>Step 6</i>
				<i>(MtCO₂e/MT) [U.S., 2015]</i>
				<i>Step 7</i>

⁶³ Algeria, Antigua and Barbuda, Argentina, Bahrain, Bangladesh, Barbados, Belize, Benin, Bolivia, Brazil, Burkina Faso, Burma, Cameroon, Chile, China, Columbia, Costa Rica, Croatia, Cuba, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Georgia, Ghana, Grenada, Guatemala, Guyana, Honduras, India, Indonesia, Iran, Jamaica, Jordan, Kenya, Lebanon, Lesotho, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritius, Mexico, Moldova, Mongolia, Morocco, Mozambique, Namibia, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Panama, Paraguay, Peru, Philippines, Saint Lucia, South Korea, Sri Lanka, Sudan, Swaziland, Syria, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Uganda, Uruguay, Venezuela, Vietnam, Yemen, Zambia, and Zimbabwe.

This methodology is followed for each country, given year, and end-use category (e.g., refrigeration). This equation thus produces preliminary estimates based on the general assumption that all countries will transition away from ODSs in a similar manner as the United States. (For example, CFC-12 mobile air-conditioners transitioned to HFC-134a beginning in 1994 in the United States. Thus, as a first estimation, it was assumed that CFC-12 mobile air-conditioners transition to HFC-134a in other countries.) In many cases, options for ODS substitutes in each end use are technically limited to the same set of alternatives, regardless of geographic region. Furthermore, alternative technologies used in the United States are available and in many cases are used worldwide. These assumptions may be adjusted in later steps to account for differences between the United States and other countries, as explained below.

8. *Develop and apply adjustment factors.* In this analysis, the EPA applied adjustment factors to modify the emission estimates for countries based on what is known qualitatively about how their transition to alternatives and technology preferences will likely differ from that of the United States. For example, the EPA multiplied the estimates produced in Step 7 by adjustment factors of less than 1 to refrigeration and AC end uses because some nations have been more likely to use hydrocarbon (HC) refrigerants than HFCs and/or because some nations may choose less emissive designs or practices. Table 5-36 shows the adjustment factors used for each sector and country grouping.

Table 5-36: Adjustment Factors Applied in by Sector and Country

Country	Ref/AC	Sector			
		Aerosols	Foams	Solvents	Fire-Ext.
Australia/New Zealand	0.90	1.00	1.00	1.00	1.00
China/economies in transition	0.80	1.00	1.00	1.00	1.00
EU	0.70	1.00	1.00	1.00	1.00
Non-EU Europe	0.80	1.00	0.00	1.00	1.00
Japan	0.70	1.00	1.00	1.00	1.00
Rest of World	0.80	1.00	0.00	1.00	1.00

Projected

The following general steps were applied to project country-specific emissions following the adjustments in the steps above.

9. *Develop timing factors.* Because most developing countries will transition to substitutes more slowly, the EPA reduced the adjusted emission estimates by multiplying the results in each year by a timing factor to reflect the assumed delay in their transition. In the Montreal Protocol, developing countries are listed under Article 5.⁶⁴ Timing factors for CFCs start at 25% in 1995 and increase by 25% at each 5-year interval, until they reach 100% in 2010, consistent with the Montreal Protocol data for their CFC phaseout and when they are assumed to have caught up to the developed countries. Article 5 countries also have a delayed phase-out of HCFCs to account for the fact that these countries can continue consuming new HCFCs through 2040 with specific step-downs based on the 2007 Adjustment to the Montreal Protocol. These factors are outlined in Table 5-37.

⁶⁴ A complete list of Article 5 countries is available at http://ozone.unep.org/Ratification_status/list_of_article_5_parties.shtml.

Table 5-37: Timing Factors Used for Developing (Article 5) Countries

Factor	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
CFCs	0.25	0.50	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HCFCs	0.00	0.00	0.00	0.00	0.11	0.35	0.68	0.98	0.98	1.00	1.00	1.00

10. *Develop economic growth factors.* Because other countries' economies are growing at different rates than the United States' economy, the EPA altered emissions based on comparisons between U.S. and regional historical and projected GDP. These GDP growth factors are shown in Table 5-38.

Table 5-38: GDP Growth Factors (relative to U.S.)

Region	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Africa	0.92	0.89	1.02	1.26	1.31	1.39	1.50	1.61	1.69	1.76	1.82	1.87
Asia	1.23	1.14	1.28	1.60	1.83	2.09	2.37	2.69	2.86	3.04	3.22	3.41
Australia/New Zealand	0.99	0.98	1.02	1.12	1.15	1.19	1.21	1.23	1.27	1.31	1.35	1.40
Brazil	1.02	0.92	0.94	1.12	1.06	1.00	1.04	1.06	1.09	1.12	1.15	1.18
Canada	0.96	0.95	0.95	0.97	0.96	0.96	0.96	0.95	0.95	0.95	0.95	0.97
Central/South America	1.10	1.00	1.03	1.24	1.30	1.29	1.35	1.43	1.48	1.53	1.58	1.63
China	1.57	1.92	2.70	4.44	5.81	6.99	8.06	9.27	9.87	10.53	11.00	11.21
Eastern Europe	0.46	0.39	0.48	0.54	0.47	0.48	0.51	0.54	0.56	0.58	0.60	0.62
Economies in Transition	0.55	0.48	0.57	0.65	0.62	0.58	0.57	0.57	0.57	0.55	0.51	0.49
EU	0.95	0.89	0.86	0.87	0.82	0.80	0.78	0.76	0.75	0.75	0.74	0.74
Europe (non-EU)	0.95	0.89	0.86	0.90	0.87	0.85	0.84	0.83	0.82	0.81	0.81	0.81
India	1.13	1.23	1.50	2.15	2.67	3.49	4.53	5.68	6.64	7.66	8.74	9.84
Japan	0.94	0.80	0.75	0.73	0.68	0.63	0.59	0.56	0.53	0.51	0.50	0.48
Mexico	0.98	1.01	0.97	1.03	1.06	1.09	1.14	1.19	1.27	1.38	1.51	1.63
Middle East	0.97	0.97	1.09	1.33	1.42	1.51	1.61	1.72	1.80	1.87	1.93	1.98
South Korea	1.29	1.34	1.49	1.76	1.83	1.89	1.90	1.89	1.88	1.87	1.86	1.86

Source: USDA (2017).

11. *Estimate adjusted HFC emissions in metric tons of CO₂ equivalent in a given year by country.* The EPA estimated emissions and projections for each year by multiplying the estimates in Step 7 by the adjustment factors (Step 8), the timing factors (Step 9), and the growth factors (Step 10).

Country-Specific Adjustments

Nations that have ratified the Montreal Protocol are required to report ODS consumption by chemical "group" (e.g., CFCs) to the UNEP Ozone Secretariat; as of this report, all 197 nations and the European Union had ratified the Montreal Protocol. Where available, EPA made country-specific adjustments using reported HFC consumption data published by the MLF for 77 low volume consuming (LVC) and 42 non-LVC countries (UNEP, 2017b).

For countries included in the MLF study, 2015 HFC consumption estimates replace the country-specific HFC consumption estimates developed under Steps 1 through 4 using ODS consumption data. Total HFC consumption for the 77 LVC and 42 non-LVC countries in 2015 was disaggregated by country using each country's relative 2012 HCFC consumption (UNEP, 2017b). Consumption estimates for each country were further disaggregated by sector based on reported survey data. Consumption estimates from 1990 through 2050 were then determined for each year by back- and forecasting consumption from the 2015 estimate (by applying the economic growth factors developed in Step 10) and then emissions were estimated using the approach outlined in Step 11.

Emission Factors

In addition to the adjustments discussed above, the EPA adjusted the methodology for some sectors to account for information that was available on a country or regional scale. These adjustments are discussed by sector in more detail below.

Historical and Projected

Fire Extinguishing

The EPA adjusted global emissions in the fire extinguishing sector by region by developing Vintaging Model scenarios that were representative of country- and region-specific substitution data. In addition, the EPA adjusted emissions in the EU to account for the rapid halon phase-out due to regulation. Details of these adjustments include the following:

- To estimate baseline emissions, information collected on current and projected market characterizations of international total flooding sectors was used to create country-specific versions of the Vintaging Model (i.e., country-specific ODS substitution patterns). For this report, current and projected market information was obtained on new total flooding systems in which halons have been previously used. Information for Australia, Brazil, China, India, Japan, Russia, and the UK was obtained from Halon Technical Options Committee members from those countries.⁶⁵ Information for the United States was taken from the Vintaging Model. General information was also collected on northern, southern, and eastern Europe. Baseline emission information from some of these countries was used to adjust the substitution patterns for all other countries not listed above, as described below:
 - Australia: proxy for New Zealand
 - Brazil: proxy for countries in Latin America and the Caribbean
 - India: proxy for all other developing countries
 - Eastern, northern, and southern Europe: proxies for European countries (based on geography)
 - Russia: proxy for economies in transition

An adjustment factor was applied to EU countries to account for European Regulation 2037/2000 on Substances that Deplete the Ozone Layer, which mandates the decommissioning of all halon systems and extinguishers in the EU-15 by the end of 2003 (with the exception of those applications that are defined as critical uses). To reflect this, the methodology assumed that all halon systems in the EU-15 will be decommissioned by 2004. No adjustments were made to the 13 countries that joined the EU since May 2004, because the regulation makes exceptions for these countries.

Refrigeration and Air-Conditioning

The EPA adjusted estimates for the refrigeration and AC sector to account for less refrigerant recovery (i.e., more venting) in developing countries. These estimates assumed that recovery does not occur in these countries in

⁶⁵ Fire protection experts in these countries provided confidential information on the status of national halon transition markets and average costs to install the substitute extinguishing systems in use (on a per volume of protected space basis) for 2001 through 2020.

any small refrigeration and AC units but does occur in larger units, such as chillers. The resulting adjustment factors are shown in Table 5-39.

Table 5-39: Recycling Adjustment Factors Applied to Refrigeration Emission Estimates

Year	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Adjustment factor	1.00	1.01	1.03	1.09	1.12	1.28	1.51	1.77	1.79	1.74	1.69	1.68

Aerosols

Because the ban on CFC use in MDI aerosols caused the United States to transition out of CFCs earlier than other countries, the U.S. consumption of ODSs in 1990 for non-MDI aerosols was assumed to be zero. To determine a nonzero denominator for the ratio calculated in Step 4, it was assumed that 15% of the non-MDI aerosols ODS consumption transitioned to HFCs, while the remainder was assumed to transition to not-in-kind (NIK) or HC alternatives.

Foams

Most global emissions were estimated in the foam-blowing sector by developing Vintaging Model scenarios that were representative of country- or region-specific substitution and consumption patterns. To estimate baseline emissions, current and projected characterizations of international total foams markets were used to create country- or region-specific versions of the Vintaging Model. The market information was obtained from Ashford (2004), based on research conducted on global foam markets. Scenarios were developed for Japan, Europe (both EU and non-EU countries combined), other developed countries (excluding Canada), countries with economies in transition, and China. It was assumed that other Non-A1 countries would not transition to HFCs during the scope of this analysis, as reflected by the foams adjustment factor (Step 8 above). Once the Vintaging Model scenarios had been run, the emissions were disaggregated to a country-specific level based on estimated 1989 CFC consumption for foams developed for this analysis. Emission estimates were adjusted slightly to account for relative differences in countries' economic growth as compared with the United States (Step 10 above).

Emission Reductions in the Baseline Scenario

For this analysis, the model calculated a BAU case that does not incorporate measures to reduce or eliminate the future emissions of these gases, other than those regulated by U.S., EU, Australian, Canadian, and Japanese law. For the United States, the Vintaging Model includes transitions to low-GWP alternatives to reflect compliance with rules issued under EPA's Significant New Alternatives Policy Program.⁶⁶ For the EU, the HFC consumption reduction schedule from the F-GHG regulations was applied evenly, starting in 2015, to the consumption estimates across all countries in the EU and across all sectors. For Australia and Canada, the reduction schedule from their F-GHG regulations was applied evenly, starting in 2020, to the consumption estimates. For Japan, consumption estimates have been adjusted according to mandated transitions to alternatives with GWPs below a target threshold in select refrigerants/AC, foam, and aerosol propellants end uses. No other F-GHG policies have been applied.

Furthermore, the model does not project future market transitions, including those anticipated by industry. There is significant uncertainty as to what compounds will replace HFCs in ODS substitutes' applications, particularly in developing countries.

Uncertainties

ODSs and their substitutes are first consumed during manufacture (e.g., to charge a refrigerator). These gases are then mostly emitted to the atmosphere over time from equipment leaks, services, and disposal. Some

⁶⁶ At the time of publication, the Court of Appeals for the District of Columbia Circuit vacated these rulemakings.

consumption may be recovered or recycled, depending on the end use and country. The relationship between initial consumption and eventual emission is complex and uncertain.

5.2.8.2 Mitigation Options Considered

Refrigeration and AC Mitigation Options Considered

A number of HFCs are used in refrigeration and AC systems and are emitted to the atmosphere during equipment operation, repair, and disposal, unless recovered, recycled, and ultimately destroyed. The most common HFCs are HFC-134a, R-404A, R-410A, R-407C, and R-507A.⁶⁷ In response to the ODS phaseout, equipment is being retrofitted or replaced to use HFC-based substitutes or intermediate substitutes (e.g., HCFCs) that will eventually need to be replaced by HFCs or other non-ozone-depleting alternatives.

This analysis considered reduction costs for applying 19 new technologies and using three types of improved technician practices. Table 5-40 summarizes the technology and practice options reviewed, the types of equipment that were assumed to adopt such options, and the associated system type definitions (i.e., the equipment characteristics assumed to develop the option costs).

Table 5-40: Refrigeration and AC Abatement Options

Abatement Option	Reduction Efficiency	Applicability
HFO-1234yf in MVACs	100%	New MVACs in light-duty vehicles
R-513A in buses and trains	57%	New AC systems in buses and trains
R-407A/R-407F in new large retail food	50%	New large retail food refrigeration systems
HFC secondary loop and/or cascade systems in new large retail food	50%	New large retail food refrigeration systems
CO ₂ transcritical systems in new large retail food	100%	New large retail food refrigeration systems
CO ₂ in medium retail food refrigeration systems	100%	New medium retail food refrigeration systems
HC in ice makers	100%	New ice makers
R-452A in refrigerated trucks/trailers and intermodal containers	45%	New refrigerated trucks/trailers and intermodal containers
NH ₃ or CO ₂ in large refrigeration systems	100%	New industrial process refrigeration (IPR) and cold storage systems
HCs in new domestic refrigeration	100%	New domestic refrigerators
MCHX in new commercial unitary AC systems	37.5%	New commercial unitary AC equipment
R-32 in new commercial unitary AC Equipment	67%	New commercial unitary AC equipment
R-32 with MCHX in new commercial unitary AC	87%	New commercial unitary AC equipment
R-452B with MCHX in new residential and commercial unitary AC	87%	New residential unitary AC equipment

(continued)

⁶⁷ 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.

Table 5-40: Refrigeration and AC Abatement Options (continued)

Abatement Option	Reduction Efficiency	Applicability
R-290 in new residential unitary ac equipment	100%	New residential unitary AC equipment
R-452B in new heat pumps	67%	New heat pumps
HCs in new window ac and dehumidifiers	100%	New window AC and dehumidifiers
R-32 in new window ac and dehumidifiers	68%	New window AC and dehumidifiers
R-452B in new positive displacement chillers	64%	New positive displacement chillers
R-450A/R-513A in new centrifugal chillers	57%	New centrifugal chillers
HCFO-1233zd(E) in new centrifugal chillers	99%	New centrifugal chillers
Leak repair	40%	All existing large equipment (i.e., large retail food, IPR, cold storage, and chillers)
Refrigerant recovery at servicing	95%	All small equipment (i.e., MVACs, unitary AC)
Refrigerant recovery at disposal	85%	All existing refrigeration/AC reaching disposal

HFO-1234yf in New MVACs

Hydrofluoroolefin (HFO)-1234yf has a GWP of only 4 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 of models (*Refrigeration and Air Conditioning Magazine*, 2013). This option was 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 developing countries because it was assumed to penetrate the baseline market in the EU and other developed countries.

- **Capital Cost:** The one-time capital cost was estimated at approximately \$110 per MVAC system, resulting from incremental refrigerant costs and hardware changes (EPA and NHTSA, 2011; Centro Ricerche Fiat, 2008). The hardware costs were assumed to be 10% greater in developing countries.
- **Annual O&M Costs:** Annual costs were assumed to be approximately \$3 per system associated with incremental refrigerant replacement costs.
- **Annual Revenue:** No annual savings were assumed.

R-513A in New Buses and Trains

This abatement option applies to the use of R-513A, a nonflammable blend of HFC-134a and HFO-1234yf in AC systems for buses and trains. The refrigerant charge size for bus and train AC systems is much larger than for light-duty vehicle and car MVACs; therefore, the use of flammable or mildly flammable alternatives is more of a concern (UNEP 2018). Although the use of HFO-1234yf in buses and trains has been modeled in the past, HFO-1234yf is not a likely option because it is flammable and egress options are limited. This option is applicable to newly manufactured AC systems in buses and trains in developed and developing countries.

- **Capital Cost:** R-513A is very similar to HFC-134a, such that existing equipment requires little to no change to achieve the desired operational characteristics. Therefore, no one-time costs were assumed.
- **Annual O&M Costs:** Annual costs were assumed to be approximately \$9 per system associated with incremental refrigerant replacement costs.
- **Annual Revenue:** No annual savings were assumed.

R-407A/R-407F in New Large Retail Food

This abatement option was applied to a newly manufactured large retail food system in a large supermarket. This option replaces HFC refrigerant blends of R-404A and R507A with lower GWP HFC refrigerant blends R-407A and R-407F, which requires little to no change to achieve the desired operational characteristics. When designing new systems, additional modifications may be needed, such as changing the orifice or thermostatic expansion valve size to achieve the same efficiency (ACHR News, 2012). In addition, HFC refrigerant blends R-407A and R-407F offer a 10% to 15% increase in energy efficiency compared with R-404A (Linde Gas, 2014; Honeywell, 2014). This option is applicable to newly manufactured large retail food systems in developing countries because this transition is assumed to have largely occurred in developed countries.

- **Capital Cost:** R-404A and R-507A are very similar to R-407A and R-407F in their key chemical properties, such that existing equipment requires little to no change to achieve the desired operational characteristics. Therefore, no one-time costs were assumed.
- **Annual O&M Costs:** R-404A and R-507A have prices roughly equal to R-407A and R-407F. Therefore, this analysis assumed no annual costs are incurred when transitioning to these alternative refrigerants.
- **Annual Revenue:** Annual savings are estimated to equal almost \$17,200 per supermarket, associated with reduced energy consumption of 12.5% compared with a baseline energy usage of 1.2 million kWh/year and assuming electricity cost savings are 66% greater for developing countries.

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 CO₂ commonly used in the low-temperature circuit and an HFC used as the refrigerant at the medium-temperature phase (Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee, 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 just as efficient as conventional DX systems, if not more so, because of simplified piping, newly designed circulating pumps, and fewer components (Wang et al., 2010; DelVentura et al., 2007; Heath and Armer, 2012; WalMart, 2006; Hinde, Zha, and Lan, 2009). In addition, HFC refrigerant blends R-407A and R-407F offer up to a 15% increase in energy efficiency compared with R-404A (Linde Gas, 2014; Honeywell, 2014).

This abatement option was applied to a newly manufactured large retail food system in a large supermarket.

- **Capital Cost:** The one-time cost in developed countries was estimated to be up to 25% more expensive than conventional DX systems (IPCC, 2005); it was assumed that conventional DX systems cost roughly \$182,000 for a large (60,000 sq. ft.) supermarket. The incremental increase is, therefore, approximately \$45,500 per supermarket; this capital cost was estimated to be 10% greater in developing countries.
- **Annual O&M Costs:** This analysis did not assume O&M costs.
- **Annual Revenue:** Secondary loop systems were assumed to reduce annual direct emissions by reducing charge size by 70% and reducing the annual leak rate from 15% to 5%. Annual savings are estimated to equal almost \$4,600 per supermarket associated with reduced refrigerant charge and leakage and reduced energy consumption of 5% compared with a baseline energy usage of 1.2 million kWh/year;

annual electricity cost savings were assumed to be 66% greater for developing countries, resulting in annual savings of approximately \$7,300.

CO₂ Transcritical Systems in New Large Retail Food

This option eliminates the use of HFCs in large retail food refrigeration systems through the use of CO₂ as the primary refrigerant in a transcritical cycle. CO₂ transcritical systems are similar to traditional centralized DX designs but must operate at high pressures to accommodate the low critical temperature of CO₂ (GTZ Proklima, 2008). As a result, special controls and component specifications must be incorporated into the system design, which often results in higher upfront costs (Environmental Investigation Agency, 2012). Additionally, CO₂ 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, because of a possible energy penalty, the use of CO₂ 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). In 2012, it was estimated that over 1,300 CO₂ transcritical systems were 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). In 2018, it was reported that 196 U.S. supermarkets within the GreenChill partnership used CO₂ transcritical systems (R744, 2019a).

This abatement option was assumed to be applied to a newly manufactured large retail food system in large supermarkets in cooler climates in developed and developing countries.

- **Capital Cost:** One-time costs for CO₂ transcritical systems in developed countries are estimated to be 17.5% more expensive than conventional HFC centralized DX systems (Australian Green Cooling Council, 2008; R744, 2012); it was assumed that conventional DX systems cost roughly \$182,000 for a large (60,000 sq. ft.) supermarket, equivalent to an incremental cost of nearly \$32,000 per supermarket; these capital costs are estimated to be 10% greater in developing countries.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** Annual savings are estimated at about \$13,400 per supermarket, which results from both refrigerant savings (due to avoided HFC refrigerant leaks) that total approximately \$1,800 per supermarket and energy savings (due to increased efficiency) that total approximately \$11,600 per supermarket. In developing countries, where electricity rates were assumed to be 66% higher, annual savings were assumed to total more than \$21,100.

CO₂ in Medium Retail Food Refrigeration Systems

This option eliminates the use of HFCs in medium retail food refrigeration systems and condensing units through the use of CO₂ as the primary refrigerant in a transcritical cycle. Although CO₂ transcritical systems are typically used in large retail food systems, CO₂ provides an opportunity for reductions at smaller stores, such as convenience stores or smaller grocery stores in city-center locations. CO₂ systems are similar to traditional HFC designs but must operate at high pressures to accommodate the low critical temperature of CO₂ (GTZ Proklima, 2008). These systems are often referred to as mini-boosters. As a result, special controls and component specifications must be incorporated into the system design, which often results in higher upfront costs (Environmental Investigation Agency, 2012). These systems have already been launched in Japan and Europe, with capacities of 2 to 10 kW, suitable for small supermarkets and convenience stores (R744, 2019b).

This abatement option applies the use of CO₂ in refrigeration systems for medium retail food equipment as a replacement for R-404A or R-507A. This option is applicable to newly manufactured refrigeration systems in all countries.

- **Capital Cost:** One-time savings are estimated at approximately \$110 per system associated with incremental refrigerant costs. Additional costs may be realized associated with designing a system to operate at a higher pressure, but they were not quantified in this analysis.
- **Annual O&M Costs:** No annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are estimated at about \$13 per system associated with incremental refrigerant replacement costs. Annual energy savings are also likely to be associated with this option, but they were not quantified in this analysis.

R-290 in New Ice Makers

This abatement option was applied to the use of R-290 as a replacement for HFC-134a or R-404A in ice makers. Ice makers generate ice by freezing water as a stand-alone appliance or an industrial machine for making ice on a large scale. Ice makers with R-290 are designed with separate specifications from HFC equipment because of its flammability. Some ice maker manufacturers, for example, Hoshizaki in Japan, have pledged to transition to R-290 refrigerant by 2018 (Hydrocarbons21, 2016).

This option is applicable to newly manufactured ice makers in all countries, except the EU, where it was already assumed to penetrate the baseline market. For cost modeling purposes, this option was applied to a manufacturing facility that produces 10,000 ice makers per year.

- **Capital Cost:** The one-time capital cost was estimated at approximately \$325,000 per facility, resulting from the additional structural and safety precautions applied to the design of equipment using flammable refrigerants, including purchasing new charging equipment, testing and certifying equipment to the appropriate safety standards, and converting manufacturing facilities to accommodate a flammable refrigerant, if applicable (e.g., installing sensors and storage capacity).
- **Annual O&M Costs:** No annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are estimated at about \$9,600 per facility associated with incremental refrigerant replacement costs.

R-452A in New Refrigerated Trucks and Trailers

This abatement option was applied to the use of R-452A as a replacement for refrigerated trucks/trailers and intermodal containers. Refrigerated trucks/trailers and intermodal containers are designed to carry perishable freight at specific cold temperatures. R-404A is the most used refrigerant in transport refrigeration today. R-452A, an HFO blend with significantly lower environmental impacts, is considered a drop-in replacement for R-404A. R-452A has been tested in refrigerated transport applications and showed no loss of performance and reliability in terms of refrigeration capacity, pull-down, and fuel efficiency (Thermo King, 2014). This option is applicable to newly manufactured systems in all countries.

- **Capital Cost:** R-452A is very similar to R-404A, such that existing equipment requires little to no change to achieve the desired operational characteristics. Therefore, no one-time costs associated with equipment modifications were assumed. A one-time cost equal to roughly \$83 per system was assumed because of the incremental refrigerant cost.
- **Annual O&M Costs:** Annual costs were assumed to be approximately \$28 per system associated with incremental refrigerant replacement costs.
- **Annual Revenue:** No savings were assumed.

NH₃ or CO₂ in New IPR and Cold Storage Systems

This abatement option was assumed to be applicable to cold storage and industrial process refrigeration systems. Although NH₃ refrigeration systems are already common in refrigerated spaces over 200,000 sq. ft., additional penetration of NH₃ systems is possible in facilities that are less than 200,000 sq. ft. but greater than 50,000 sq. ft. In addition, modern NH₃ 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 CO₂ systems. CO₂ systems are being used in low-temperature refrigeration (-30°C to -56°C), while ammonia/CO₂ 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 CO₂ being used on the low side. The choice between these systems is primarily due to outdoor temperatures; in colder climates, a CO₂ 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/CO₂ cascade systems. These systems are estimated to be 2% to 20% more energy efficient than their HFC counterparts (Gooseff and Horton, 2008).

- **Capital Cost:** For cost modeling purposes, this option was applied to a newly constructed IPR/cold storage refrigeration system/facility. The incremental one-time cost is estimated at approximately \$212,000 per system in developed countries (Gooseff and Horton, 2008) and assumed to be 10% more in developing countries. In addition, a one-time savings of \$18,000 was assumed due to incremental refrigerant cost.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** The annual savings of approximately \$50,200 per system was associated with lower refrigerant replacement costs and reduced energy consumption of 11%; annual electricity cost savings were assumed to be 66% greater for developing countries, resulting in annual savings of approximately \$83,000.

HCs in New Domestic Refrigeration Systems

HFC-134a may be replaced with HC_s in household refrigerators. HC_s, such as butane and propane, have very low GWPs of 4.0 and 3.3, respectively. The main disadvantage of HC_s is that they are flammable, but engineering design changes and safety features in manufacturing plants have been successfully implemented to overcome these challenges. In 2017, roughly one-third of the 100 million household refrigerators/freezers manufactured annually around the world used hydrocarbon refrigerants (Hydrocarbon21, 2017). This option is applicable to newly manufactured domestic refrigerators in developing countries because it was assumed to penetrate the baseline market in the EU and other developed countries. For cost modeling purposes, this option was applied to a manufacturing facility that produces 10,000 domestic refrigerators per year.

- **Capital Cost:** The one-time capital cost is estimated at approximately \$325,000 per facility, resulting from the additional structural and safety precautions applied to the design of equipment using flammable refrigerants, including purchasing new charging equipment, testing and certifying equipment to the appropriate safety standards, and converting manufacturing facilities to accommodate a flammable refrigerant, if applicable (e.g., installing sensors and storage capacity). In addition, a one-time savings of about \$530,000 per facility is assumed associated with incremental refrigerant replacement costs and a lower refrigerant charge size.
- **Annual O&M Costs:** No annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are estimated at about \$3,200 per facility associated with incremental refrigerant replacement costs and a lower refrigerant charge size.

MCHX in New Unitary AC Equipment

This option explores the use of microchannel heat exchangers (MCHX) in unitary AC equipment using R-410A. MCHXes 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 MCHXes 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,⁶⁸ 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 was applied to a newly manufactured small and large commercial unitary AC system.

- **Capital Cost:** A one-time savings equal to roughly \$27 was assumed because of the smaller refrigerant charge.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** The annual savings associated with avoided refrigerant losses due to a smaller refrigerant charge was estimated at approximately \$2.30 per system.

R-32 in New Commercial Unitary AC Equipment

In this option, R-32, a mildly flammable refrigerant with a GWP of 650, and R-452B, a blend of HFC-125, HFC-32, and HFO-1234yf with a GWP of 698, are used in new unitary AC equipment to replace R-410A, which has a GWP of 1,725. R-32 is category A2L in ANSI/ASHRAE Standard 34.

R-32 performs with a reduced charge volume ratio of 66% compared with R-410A (Xu et al., 2012). It is also reportedly 2% to 3% more energy efficient than R-410A (Pham and Sachs, 2010). In addition, the equipment used 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 India (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 was applied to a newly manufactured commercial unitary AC system (e.g., small commercial and large commercial unitary AC).

- **Capital Cost:** The option was conservatively assumed to result in a one-time savings of approximately \$30 per system because of the reduced quantity of refrigerant required and lower cost of the alternative refrigerant. Additional savings may be realized through reduced material costs; however, costs also may be associated with designing a system to use a mildly flammable refrigerant.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** The annual savings associated with avoided refrigerant losses due to a smaller refrigerant charge and incremental cost of replacement refrigerant was estimated at approximately \$2.30 per system. Annual energy savings are also likely to be associated with this option but were not quantified in this analysis.

R-32 with MCHX in New Commercial Unitary AC Equipment

Similar to the options described above, this option explores the use of MCHX in commercial unitary AC equipment but with R-32 refrigerant in place of R-410A. The use of 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. For cost modeling purposes, this option was applied to all newly manufactured commercial unitary AC systems.

⁶⁸ 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.

- **Capital Cost:** The option was conservatively assumed to result in a one-time savings of approximately \$46 per system because of the reduced quantity of refrigerant required and lower cost of the alternative refrigerant.
- **Annual O&M Costs:** No annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are associated with reduced charge size and incremental refrigerant replacement costs, estimated at approximately \$4 per system. Annual energy savings are also likely to be associated with this option but were not quantified in this analysis.

R-452B with MCHX in New Residential Unitary AC Equipment

Similar to the options described above, this option explores the use of MCHX in residential unitary AC equipment with R-452B refrigerant in place of R-410A. R-452B, a blend of HFC-125, HFC-32, and HFO-1234yf, has a GWP of 698 and is also category A2L in ANSI/ASHRAE Standard 34. R-452B operates at the same pressure as R-410A, even in hot climates, so no redesign is necessary; however, safety design changes may be needed (Alliance for Responsible Atmospheric Policy, 2018). R-452B performs with a reduced charge volume ratio of 90% compared with R-410A and offers slightly increased efficiency (Shen et al., 2016). The use of MCHX results in a refrigerant charge reduction of between 35% and 40% compared with conventional heat exchangers, while the use of R-452B refrigerant allows a further charge size reduction of 10% compared with R-410A.

For cost modeling purposes, this option was applied to all newly manufactured residential unitary AC systems in all countries except the EU.

- **Capital Cost:** The option was conservatively assumed to result in a one-time cost of approximately \$17 per system despite the reduced quantity of refrigerant required because of the higher cost of the alternative refrigerants. Additional costs may be realized associated with designing a system to use a mildly flammable refrigerant.
- **Annual O&M Costs:** Annual costs are associated with incremental refrigerant replacement costs, estimated at approximately \$1.40 per system.
- **Annual Revenue:** Annual energy savings are also likely to be associated with this option but were not quantified in this analysis.

R-290 in New Residential Unitary AC Equipment

This abatement option applies the use of R-290 in unitary AC equipment systems as a replacement for R-410A. Although its use is not yet widespread, Petra, a major manufacturer of HVAC equipment in the Middle East, has begun testing R-290 in large commercial HVAC systems. Petra expects that the testing will conclude in 2020 (Hydrocarbons21, 2019). In addition, both Godrej in India and Gree in China are producing units with HC refrigerants (Godrej, 2012; Gree, 2012).

This option is applicable to newly manufactured domestic refrigerators in developed and developing countries except the EU. For cost modeling purposes, this option was applied to a manufacturing facility that produces 10,000 residential unitary AC systems per year.

- **Capital Cost:** The one-time capital cost was estimated at approximately \$325,000 per facility, resulting from the additional structural and safety precautions applied to the design of equipment using flammable refrigerants, including purchasing new charging equipment, testing and certifying equipment to the appropriate safety standards, and converting manufacturing facilities to accommodate a flammable refrigerant, if applicable (e.g., installing sensors and storage capacity). In addition, a one-time savings of about \$234,000 per facility was assumed associated with incremental refrigerant replacement costs and a lower refrigerant charge size.
- **Annual O&M Costs:** No annual O&M costs were assumed.

- **Annual Revenue:** Annual savings are estimated at about \$21,000 per facility associated with incremental refrigerant replacement costs.

R-32/R-452B in New Heat Pumps

Similar to the options described above, this option explores the use of R-32 and R-452B in heat pumps in place of R-410A. For cost modeling purposes, this option was applied to all newly manufactured heat pumps in all countries.

- **Capital Cost:** The option was conservatively assumed to result in a one-time cost of approximately \$1.80 per system despite the reduced quantity of refrigerant required because of the higher cost of the alternative refrigerants. Additional costs may be realized associated with designing a system to use a mildly flammable refrigerant.
- **Annual O&M Costs:** Annual costs were associated with incremental refrigerant replacement costs, estimated at approximately \$0.44 per system.
- **Annual Revenue:** Annual energy savings are also likely to be associated with this option but were not quantified in this analysis.

R-290 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 was 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). Additionally, the first R-290-based room AC units were launched in India in 2013. Sales from launch until 2014 total over 100,000 units (NRDC, 2014).

This option is applicable to newly manufactured domestic refrigerators in developed and developing countries other than the EU. For cost modeling purposes, this option was applied to a manufacturing facility that produces 10,000 window units and/or dehumidifiers per year.

- **Capital Cost:** This option was conservatively assumed to have one-time capital costs of approximately \$325,000 per system, resulting from the additional structural and safety precautions applied to the design of equipment using flammable refrigerants, including purchasing new charging equipment, testing and certifying equipment to the appropriate safety standards, and converting manufacturing facilities to accommodate a flammable refrigerant, if applicable (e.g., installing sensors and storage capacity). 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). In addition, a one-time savings of about \$27,000 per facility was assumed associated with incremental refrigerant replacement costs and a lower refrigerant charge size.
- **Annual O&M Costs:** No annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are estimated at about \$160 per facility associated with incremental refrigerant replacement costs.

R-32 in New Window AC and Dehumidifiers

Similar to the options described above, this option explores the replacement R-410A in new window AC and dehumidifiers with R-32 refrigerant. R-32 has a lower refrigerant flow rate and a higher discharge temperature than R-410A, so some redesign is necessary. R-32 is mildly flammable and requires some safety design changes (Alliance for Responsible Atmospheric Policy, 2018). Advantages of R-32 include higher operating efficiencies, meaning units that use R-32 refrigerant consume less power than similar units with R-410A. Also, units using R-32

generally require a lower charge size, reducing the total amount of refrigerant needed. In 2016, it was estimated that more than 10 million R-32 ACs had been sold since their introduction (Proud Green Building, 2016).

This abatement option applies the use of R-32 in new window AC and dehumidifier systems. This option is applicable to newly manufactured systems in all countries except the EU.

- **Capital Cost:** The option was conservatively assumed to result in a one-time savings of approximately \$1.80 per system because of the reduced quantity of refrigerant required and lower cost of the alternative refrigerant. Additional savings may be realized through reduced material costs; however, costs also may be associated with designing a system to use a mildly flammable refrigerant.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** The annual savings associated with avoided refrigerant losses due to a smaller refrigerant charge and incremental cost of replacement refrigerant was estimated at approximately \$0.01 per system. Annual energy savings are also likely to be associated with this option but were not quantified in this analysis.

R-452B in New Positive Displacement Chillers

This abatement option applies the use of R-452B as a replacement for R-410A or R-407C in positive displacement chiller systems. R-452B is a blend of HFC-32, HFC-125, and HFO-1234yf and offers similar efficiency to R-410A units. Several equipment manufacturers offer R-452B in positive displacement chillers (Cooling Post, 2019).

- **Capital Cost:** R-452B is considered to be a drop-in replacement for R-410A; therefore, this analysis assumed no one-time equipment modification costs for transitioning to R-452B. A one-time cost of approximately \$4,200 per system associated with incremental refrigerant cost was assumed.
- **Annual O&M Costs:** This analysis assumed an annual cost of \$250 per system associated with incremental refrigerant replacement cost.
- **Annual Revenue:** This analysis did not assume a cost savings.

R-450A/R-513A in New Centrifugal Chillers

This abatement option applies the use of R-450A and R-513A in centrifugal chillers. R-450A and R-513A are blends of HFC-134a and HFO-1234yf. Equipment manufacturers in Asia offer both R-450A and R-513A centrifugal chillers (GlobeNewswire, 2018).

- **Capital Cost:** R-450A and R-513A are considered drop-in replacements for HFC-134a (Chemours, 2015); therefore, this analysis assumed no one-time equipment modification costs for transitioning to R-450A and R-513A. A one-time cost of approximately \$13,100 per system associated with incremental refrigerant costs was assumed.
- **Annual O&M Costs:** This analysis assumed an annual cost of \$780 per system associated with incremental refrigerant replacement costs.
- **Annual Revenue:** This analysis did not assume a cost savings.

HCFO-1233zd(E) in New Centrifugal Chillers

This abatement option applies the use of hydrochlorofluorolefin (HCFO)-1233zd(E) in low-pressure centrifugal chillers in place of HFC-245fa (or centrifugal chillers that historically used HCFC-123). Chiller manufacturers have already begun producing chillers with HCFO-1233zd(E). The abatement option that replaces HFC-245fa with HCFO-1233zd(E) is applicable to newly manufactured centrifugal chillers in developing countries and the EU.

- **Capital Cost:** Capital costs of \$51,000 were assumed for production line conversion to HCFO-1233zd(E), including the refrigerant system, charging machines, and safety system (UNEP, 2012). A one-time cost of approximately \$2,900 per system associated with incremental refrigerant cost was assumed.

- **Annual O&M Costs:** This analysis assumed an annual cost of \$170 per system associated with incremental refrigerant replacement costs.
- **Annual Revenue:** This analysis did not assume a cost savings.

Leak Repair for Existing Large Equipment

This abatement option was 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.

- **Capital Cost:** For cost modeling purposes, this option was 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 was estimated per supermarket for parts and labor needed to perform the repair in developed countries (EPA, 1998); in developing countries, this cost was estimated to be 10% greater.
- **Annual O&M Costs:** This analysis did not assume annual O&M costs.
- **Annual Revenue:** The annual savings associated with avoided refrigerant replacement was estimated at \$1,220 per supermarket.

Refrigerant Recovery at Servicing for Existing Small Equipment

Similar to disposal recovery, this option assumed more widespread and thorough refrigerant recovery practices while servicing HFC refrigeration/AC systems. Because it was assumed that significant refrigerant is already recovered during servicing of large equipment, this abatement option was only applied to MVAC and small unitary AC systems.

- **Capital Cost:** For cost modeling purposes, this option was 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 was estimated at approximately \$4,050 per servicing facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost was estimated to be 10% greater in developing countries.
- **Annual O&M Costs:** The annual cost was 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 were assumed to be one-fifth the cost of that in developed countries; therefore, the annual cost was assumed to be nearly \$194.
- **Annual Revenue:** The annual savings was estimated at roughly \$350 per auto servicing facility based on the value of the recovered refrigerant for reclamation/reuse.

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 United States 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 before 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,⁶⁹ or destroyed using approved technologies (e.g., incineration).

- **Capital Cost:** For cost modeling purposes, this option was applied to an auto dismantling facility assumed to use a single refrigerant recovery device that meets SAE J2788 standards to perform MVAC recovery

⁶⁹ 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.

jobs. The incremental one-time cost was estimated at approximately \$2,025 per facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost was estimated to be 10% greater in developing countries.

- **Annual O&M Costs:** 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 were assumed to be one-fifth the cost of that in developed countries; therefore, annual costs were assumed to be about \$220.
- **Annual Revenue:** The annual savings was estimated at about \$440 per auto dismantling facility based on the value of the recovered refrigerant for reclamation/reuse.

Technical and Economic Characteristics Summary

Table 5-41 presents the technical characteristics of each mitigation option considered in the analysis.

Table 5-41: Summary of Technical Characteristics of Each Mitigation Option

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
MVACs—Developing				
HFO-1234yf	46%	100%	100%	46%
Buses and Trains—U.S./Other Developed				
R-513A	21%	55%	57%	7%
Buses and Trains—EU				
R-513A	21%	55%	57%	7%
Buses and Trains—Developing				
R-513A	6%	9%	57%	0%
Large Retail Food—U.S./Other Developed				
CO ₂ transcritical systems	59%	33%	100%	19%
Large Retail Food—EU				
CO ₂ transcritical systems	59%	33%	100%	19%
Large Retail Food—Developing				
DX R-407A/R-407F	7%	34%	50%	1%
HFC secondary loop and/or cascade systems	11%	33%	50%	2%
CO ₂ transcritical systems	4%	33%	100%	1%
Medium Retail Food—U.S./Other Developed				
CO ₂ transcritical systems	44%	33%	100%	14%
Medium Retail Food—EU				
CO ₂ transcritical systems	28%	33%	100%	9%
Medium Retail Food—Developing				
CO ₂ transcritical systems	24%	33%	100%	8%
Ice Makers—U.S./Other Developed				
HCs	20%	50%	100%	10%
Ice Makers—Developing				
HCs	9%	19%	100%	2%

(continued)

Table 5-41: Summary of Technical Characteristics of Each Mitigation Option (continued)

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
Refrigerated Trucks/Trailers and Intermodal Containers—U.S./Other Developed				
R-452A	23%	50%	45%	5%
Refrigerated Trucks/Trailers and Intermodal Containers—Developing				
R-452A	0%	0%	45%	0%
IPR & Cold Storage—U.S./Other Developed				
NH ₃ or CO ₂	44%	100%	100%	44%
IPR & Cold Storage—EU				
NH ₃ or CO ₂	44%	100%	100%	44%
IPR & Cold Storage—Developing				
NH ₃ or CO ₂	19%	33%	100%	1%
Refrigerated Appliances—Developing				
HCs	7%	100%	100%	7%
Commercial Unitary AC—U.S./Other Developed				
MCHX	0%	0%	38%	11% ^c
R-32	25%	50%	68%	9%
R-32 with MCHX	5%	50%	87%	2%
Commercial Unitary AC—EU				
MCHX	0%	0%	38%	11% ^c
R-32	25%	50%	68%	9%
R-32 with MCHX	5%	50%	87%	2%
Commercial Unitary AC—Developing				
MCHX	18%	86%	38%	6%
R-32	0%	0%	68%	0%
R-32 with MCHX	0%	0%	87%	0%
Residential Unitary AC—U.S./Other Developed				
R-32/R-454B with MCHX	44%	100%	81%	13%
Residential Unitary AC—Developing				
R-32/R-454B with MCHX	0%	0%	81%	0%
R-290	0%	0%	100%	0%
Heat Pumps—U.S./Other Developed				
R-32/R-454B	10%	100%	67%	7%
Heat Pumps—EU				
R-32/R-454B	15%	100%	67%	4%
Heat Pumps—Developing				
R-32/R-454B	0%	0%	67%	0%

(continued)

Table 5-41: Summary of Technical Characteristics of Each Mitigation Option (continued)

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
Window AC Units and Dehumidifiers—U.S./Other Developed				
R-290	1%	50%	100%	1%
R-32	7%	50%	68%	2%
Window AC Units and Dehumidifiers—Developing				
R-290	4%	27%	100%	1%
R-32	4%	27%	68%	1%
PD Chillers—EU				
R-454B	28%	100%	64%	18%
PD Chillers—Developing				
R-454B	9%	100%	64%	6%
Centrifugal Chillers—EU				
R-513A	27%	100%	57%	15%
Centrifugal Chillers—Developing				
R-513A	12%	60%	57%	4%
HCFO-1233zd(E)	2%	60%	99%	1%
Cross-Cutting Practice Options—U.S./Other Developed				
Leak repair (large equipment)	51%	100%	40%	20%
Refrigerant recovery at servicing (small equipment)	10%	100%	95%	10%
Refrigerant recovery at disposal	17%	100%	85%	14%
Cross-Cutting Practice Options—EU				
Leak repair (large equipment)	61%	100%	40%	25%
Refrigerant recovery at servicing (small equipment)	12%	100%	95%	11%
Refrigerant recovery at disposal	17%	100%	85%	14%
Cross-Cutting Practice Options—Developing				
Leak repair (large equipment)	64%	100%	40%	26%
Refrigerant recovery at servicing (small equipment)	11%	100%	95%	10%
Refrigerant recovery at disposal	23%	100%	85%	20%

^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.

^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 GHG impacts (i.e., increases or decreases in electricity or fuel consumption), which were accounted for in the cost analysis.

^c This option is no longer assumed to penetrate the market in new equipment as of 2030; however, emission reductions are still experienced from existing equipment.

Table 5-42 presents the economic characteristics of each mitigation option considered in the analysis.

Table 5-42: Summary of Economic Characteristics of Each Mitigation Option

Abatement Option/Facility Type	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e) ^a
HFO-1234yf					
MVAC—Developing, new	16	\$111	—	\$3	0.2
R-513A					
Buses and trains—U.S./other developed, new	12	\$47	—	\$9	0.7
Buses and trains—EU, new	12	\$47	—	\$9	0.7
Buses and trains—Developing, new	12	\$47	—	\$9	0.7
R-407A/R-407F					
Large retail food—Developing, new	18	\$0	\$17,206	—	695.4
HFC Secondary Loop and/or Cascade Systems					
Large retail food—Developing, new	18	\$41,482	\$7,311	—	429.4
CO₂ Transcritical Systems					
Large retail food—U.S./other developed, new	18	\$19,610	\$13,445	—	1,096
Large retail food—EU, new	18	\$19,610	\$13,445	—	1,096
Large retail food—Developing, new	18	\$22,795	\$21,107	—	1,096
CO₂					
Medium retail food—U.S./other developed, existing	20	-\$108	\$13	—	8.1
Medium retail food—EU, existing	20	-\$108	\$13	—	8.1
Medium retail food—Developing, existing	20	-\$108	\$13	—	8.1
HCs					
Ice makers—U.S./other developed, new	8	\$107,125	\$9,587	—	14,213
Ice makers—Developing, new	8	\$107,125	\$9,587	—	14,213
R-452A					
Refrigerated trucks/trailers and intermodal containers—U.S./other developed, new	12	\$83	—	\$28	4.6
Refrigerated trucks/trailers and intermodal containers—Developing, new	12	\$83	—	\$28	4.6
NH₃ or CO₂					
IPR/cold storage—U.S./other developed, new	25	\$193,000	\$50,180	—	711.6
IPR/cold storage—EU, new	25	\$193,000	\$50,180	—	711.6
IPR/cold storage—Developing, new	25	\$214,100	\$82,705	—	711.6

(continued)

Table 5-42: Summary of Economic Characteristics of Each Mitigation Option (continued)

Abatement Option/Facility Type	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e) ^a
HCs					
Domestic refrigerators—Developing, new	14	-\$201,075	\$3,156	—	8,798
MCHX					
Commercial Unitary AC—U.S./other developed, new	15	-\$27	\$2	—	1.7
Commercial Unitary AC—EU, new	15	-\$27	\$2	—	1.7
Commercial Unitary AC—Developing, new	15	-\$27	\$2	—	1.7
R-32					
Commercial Unitary AC—U.S./other developed, new	15	-\$30	\$3	—	2.1
Commercial Unitary AC—EU, new	15	-\$30	\$3	—	2.1
Commercial Unitary AC—Developing, new	15	-\$30	\$3	—	2.1
R-32 with MCHX					
Commercial unitary AC—U.S./other developed, new	15	-\$46	\$4	—	2.4
Commercial unitary AC—EU, new	15	-\$46	\$4	—	2.4
Commercial unitary AC—Developing, new	15	-\$46	\$4	—	2.4
R-452B with MCHX					
Residential unitary AC—U.S./other developed, new	15	\$16	—	\$1	1.2
Residential unitary AC—Developing, new	15	\$16	—	\$1	1.2
R-290					
Residential unitary AC—Developing, new	15	\$91,250	\$21,038	—	5,915
R-32/R-452B					
Heat pumps—U.S./other developed, new	15	\$2	—	—	0.3
Heat pumps—EU, new	15	\$2	—	—	0.3
Heat pumps—Developing, new	15	\$2	—	—	0.3
HCs					
Window units/dehumidifiers—U.S./other developed, new	12	\$298,325	\$160	—	1,073
Window units/dehumidifiers—Developing, new	12	\$298,325	\$160	—	1,073
R-32					
Window units/dehumidifiers—U.S./other developed, new	12	-\$2	—	—	0.1
Window units/dehumidifiers—Developing, new	12	-\$2	—	—	0.1

(continued)

Table 5-42: Summary of Economic Characteristics of Each Mitigation Option (continued)

Abatement Option/Facility Type	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e) ^a
R-452B					
Positive displacement chiller—EU, new	20	\$4,167	—	\$250	51.1
Positive displacement chiller—Developing, new	20	\$4,167	—	\$250	51.1
R-450A/R-513A					
Centrifugal chiller—EU, new	27	\$13,057	—	\$783	73.2
Centrifugal chiller—Developing, new	27	\$13,057	—	\$783	73.2
HCFO-1233zd(E)					
Centrifugal chiller—Developing, new	27	\$53,880	—	\$173	71.7
Leak Repair					
Large retail food—U.S./Other developed, existing	5	\$1,870	\$1,224	—	533.4
Large retail food—EU, existing	5	\$1,870	\$1,224	—	533.4
Large retail Food—Developing, existing	5	\$2,057	\$1,224	—	533.4
Recovery at Servicing					
Auto servicing station—U.S./other developed	7	\$4,050	\$351	\$870	62.8
Auto servicing station—EU	7	\$4,050	\$351	\$870	62.8
Auto servicing station—Developing	7	\$4,455	\$351	\$174	62.8
Recovery at Disposal					
Auto disposal yard—U.S./other developed	7	\$2,026	\$445	\$1,084	79.6
Auto disposal yard—EU	7	\$2,026	\$445	\$1,084	79.6
Auto disposal yard—Developing	7	\$2,229	\$445	\$217	79.6

^aEmission reductions shown include only reductions associated with HFCs; they do not include indirect (CO₂) emissions associated with differences in energy consumption.

Sector-Level Trends/Considerations

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 conservative. Moreover, new options not quantified in this analysis are entering the market and will continue to do so; additional options, such as CO₂ in transport refrigeration and low-GWP refrigerants for comfort cooling chillers, could be quantitatively considered in future analyses.

The costs for the options explored in this analysis are highly variable, depending on the types of systems reviewed. 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, determining an

average cost of such repairs or the average emission reduction associated with them is difficult. 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 was assumed that numerous abatement options result in increased or decreased energy consumption (e.g., R-407A/R-407F in large retail food refrigeration systems, CO₂ transcritical large retail food refrigeration systems, NH₃ or CO₂ in new IPR and cold storage systems). While the cost associated with the increase or decrease in energy consumption, which would vary widely based on region as well as particular application, was quantified as part of this analysis, the increase or decrease in CO₂ emissions associated with this energy use was 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.

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Solvent Use Mitigation Options Considered

Historically, CFCs (in particular CFC-113), methyl chloroform, and, to a lesser extent, carbon tetrachloride were used as the predominant solvent cleaning agents. HFCs, hydrofluoroethers (HFEs), PFCs, and aqueous and semi-aqueous NIK solvents have since replaced these legacy solvents, with HFC emissions currently dominating the GWP-weighted emissions from the solvents sector.

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. This section briefly describes each option. Table 5-43 provides a technology overview of each abatement option in terms of its assumed reduction efficiency and applicability by facility type.

Table 5-43: Solvent Use Abatement Options

Abatement Option	Reduction Efficiency	Applicability
HFC to HFE	76.4%	All facilities
Retrofit	50.0%	Nonretrofitted facilities
NIK aqueous	100.0%	Electronics cleaning
NIK semi-aqueous	100.0%	Electronics cleaning

For the purposes of evaluating the cost of reducing HFC emissions, this analysis characterized four model facilities of emission sources:

Precision cleaning applications with retrofitted equipment: Precision cleaning may apply to electronics components; medical devices; or metal, plastic, or glass surfaces and is characterized by applications that require a high level of cleanliness to ensure the satisfactory performance of the product being cleaned. This facility is defined as a vapor degreaser that is 10 sq. ft. in size, uses HFC-4310mee as a solvent, and emits approximately 250 pounds of solvent annually (Owens, 2008). The facility was assumed to have already retrofitted its equipment through engineering control changes and improved containment to minimize emissions to comply with stringent environmental and safety regulations (e.g., the National Emissions Standards for Hazardous Air Pollutants [NESHAPs] in the United States) that limit emissions from solvent cleaning equipment in the United States and other developed countries.

Precision cleaning applications with nonretrofitted equipment: This facility is characterized to generally distinguish between precision cleaning facilities in developed and developing countries. The degreaser size and type of solvent used are identical to the precision cleaning facility mentioned above; however, this facility is assumed to not have retrofitted equipment to better control emissions because of the lack of regulations requiring such controls. Thus, the amount of HFC solvent lost annually is higher; this analysis assumed a loss of approximately 500 pounds annually for this facility based on the assumption that retrofitted equipment emits 50% less than nonretrofitted equipment (Durkee, 1997).

Electronics cleaning applications with retrofitted equipment: Electronics cleaning, including defluxing and other cleaning operations, is defined as a process that removes contaminants, primarily solder flux residues, from electronics and circuit boards. This facility is defined as a vapor degreaser 10 sq. ft. in size, which uses HFC-4310mee as a solvent and emits approximately 250 pounds of solvent annually (Owens, 2008). Similar to the precision cleaning applications with equipment retrofits, this facility was assumed to have already retrofitted its equipment through engineering control changes and improved containment to minimize emissions because of regulations in place to control VOC emissions.

Electronics cleaning applications with nonretrofitted equipment: This facility is characterized to generally distinguish between electronics cleaning facilities in developed and developing countries. The degreaser size and type of solvent used by this facility are identical to the electronics cleaning facility mentioned above; however, this facility was assumed to not have retrofitted equipment to better control emissions because of the lack of regulations requiring such controls. This analysis assumed emissions of approximately 500 pounds annually from this facility based on the assumption that retrofitted equipment emits 50% less than nonretrofitted equipment (Durkee, 1997).

HFCs to HFEs

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 were 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-7200.⁷⁰ For the purpose of this analysis, the 100-year GWP of alternative solvents was calculated as the weighted average of 75% HFE-7100 with a GWP of 297 and 25% HFE-7200 with a GWP of 59 for a GWP of 238.

- **Capital Cost:** HFE solvents are very similar to HFC-4310mee in their key chemical properties, such that existing equipment designed with low emission features can still be used with HFE solvents, although the equipment might need minor adjustments, such as resetting of the heat balance. These modifications are not likely to amount to a substantial one-time cost (ICF Consulting, 2003; Owens, 2003); therefore, this analysis assumed no one-time costs for converting to an HFE solvent.
- **Annual O&M Costs:** HFE solvents have pricing structures roughly equal to the pricing structure of HFCs (Owens, 2003). Therefore, this analysis assumed no annual costs are incurred when transitioning to an HFE solvent.
- **Annual Revenue:** This analysis did not assume a cost savings. A net cost savings may occasionally be experienced by end users that choose HFE solvents that are lower in density than HFC-4310mee (Owens, 2003). For example, because the same volume of solvent is used and solvents are sold on a mass basis, formulations blended with HFE-7200 may be lower in cost relative to formulations containing HFC-4310mee.

Retrofit

This abatement option is applicable to nonretrofitted facilities using solvents for 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 O&M, 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 this analysis, the reduction efficiency of the retrofit option was assumed to equal 50%.

In the United States, many enterprises have bought new equipment or retrofitted aging equipment into compliance with the 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

⁷⁰ 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.

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 assumed that end 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-A1 (i.e., developing) countries were 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.

- **Capital Cost:** To retrofit equipment, significant upgrades must be made. One-time costs were based on the assumption that a user chooses to retrofit their equipment through increasing freeboard height, installing a cover, and installing a freeboard refrigeration device. Based on these upgrades, one-time costs were assumed to be \$24,500 (Durkee, 1997).
- **Annual O&M Costs:** No annual costs are associated with this abatement option.
- **Annual Revenue:** Annual savings are associated with the avoided consumption of HFC that results from a reduction in emissions. An annual cost savings of almost \$4,500 was assumed based on the assumed reduction in emissions of 250 pounds per year of HFCs that would otherwise need to be replaced.

NIK 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 electronics 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%.

- **Capital Cost:** Vapor degreasers are not suitable for retrofit to aqueous cleaning processes (Crest Ultrasonic, 2008). Therefore, the cost of replacing an HFC-containing cleaning system with an aqueous system was based on the initial investment in tanks, equipment, and space (Beeks, 2008). This analysis assumed a one-time cost of \$50,000 for the investment in the equipment and the additional space needed for that equipment (Owens, 2008).
- **Annual O&M Costs:** The major operating costs for an aqueous system are associated with the cost of energy and the cost of the continuous flow of de-ionized water (Crest Ultrasonic, 2008). An annual cost of \$7,400 was used to represent energy and water consumption costs; this cost was based on consumption of 9 kilowatt (kW) per day and \$10 worth of de-ionized water per day (Owens, 2008).
- **Annual Revenue:** Annual savings were based on the savings associated with not using an HFC-based cleaning system. An annual savings of \$6,700 was used to represent energy and HFC solvent cleaner costs associated with using a retrofitted HFC-based cleaning system, while an annual savings of \$11,200 was used to represent energy and HFC solvent cleaner costs associated with using a nonretrofitted HFC-based cleaning system; this savings was based on consumption of 4 kW per day and 250 to 500 pounds of HFC lost per year (Owens, 2008; Durkee, 1997).

NIK 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 electronics 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%.

- **Capital Cost:** Compared with aqueous systems, semi-aqueous systems often require an extra tank or two as well as the need for ventilation. Therefore, semi-aqueous systems were assumed to be slightly higher in cost than aqueous systems (Crest Ultrasonic, 2008). Additionally, vapor degreasers are not suitable for retrofit to semi-aqueous cleaning processes (Crest Ultrasonic, 2008). Therefore, the cost of replacing an HFC-containing cleaning system with a semi-aqueous system was based on the total initial investment in tanks and equipment (Beeks, 2008). This analysis assumed a one-time cost of \$55,000 for the investment in the equipment and the additional space needed for that equipment (Owens, 2008).⁷¹
- **Annual O&M Costs:** The major operating costs for a semi-aqueous system are associated with the cost of energy and the cost of the continuous flow of de-ionized water. Compared with aqueous systems, semi-aqueous systems add a level of complication and were, therefore, assumed to require more energy. As a result, an annual cost of \$9,100 was used to represent energy and water consumption costs; this cost was based on consumption of 12 kW per day and \$10 worth of de-ionized water per day (Owens, 2008).
- **Annual Revenue:** Annual savings are based on the savings associated with not using an HFC-based cleaning system. An annual savings of \$6,700 was used to represent energy and HFC solvent cleaner costs associated with using a retrofitted HFC-based cleaning system, while an annual savings of \$11,200 was used to represent energy and HFC solvent cleaner costs associated with using a nonretrofitted HFC-based cleaning system; this savings was based on consumption of 4 kW per day and 250 to 500 pounds of HFC lost per year (Owens, 2008; Durkee, 1997).

Technical and Economic Characteristics Summary

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter required making several 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 5-44 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

Table 5-44: Technical Effectiveness Summary—Solvent Use

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
Precision Retrofitted—U.S. and Other Developed and EU				
HFC to HFE	60%	87%	85%	44%
Precision Nonretrofitted—Developing				
HFC to HFE	60%	65%	85%	26%
Retrofit	100%	18%	50%	14%
Electronics Retrofitted—U.S. and Other Developed and EU				
HFC to HFE	100%	67%	85%	57%
Aqueous	100%	7%	100%	7%
Semi-aqueous	100%	7%	100%	7%

(continued)

⁷¹ Although these costs are higher than the NIK aqueous abatement option, it was 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.

Table 5-44: Technical Effectiveness Summary—Solvent Use (continued)

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
Electronics Nonretrofitted—Developing				
HFC to HFE	100%	20%	85%	17%
Retrofit	100%	16%	50%	8%
Aqueous	100%	2%	100%	2%
Semi-aqueous	100%	2%	100%	2%

^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.

^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 GHG impacts associated with decreased electricity consumption (e.g., aqueous and semi-aqueous cleaning), which are accounted for in the cost analysis.

Table 5-45 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price. This section provides additional detail on the base cost estimates.

Table 5-45: Engineering Cost Data on a Facility Basis—Solvent Use

Abatement Option	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e)
HFC to HFE					
Retrofitted—Developed	15	—	—	—	159
Nonretrofitted—Developing	15	—	—	—	191
Inert gas					
Nonretrofitted—Developing	15	\$24,500	\$4,500	—	186
NIK aqueous					
Retrofitted—Developed	15	\$50,000	\$6,700	\$7,400	186
Nonretrofitted—Developing	15	\$50,000	\$11,200	\$7,400	224
NIK semi-aqueous					
Retrofitted—Developed	15	\$55,000	\$6,700	\$9,100	186
Nonretrofitted—Developing	15	\$55,000	\$11,200	\$9,100	224

Sector-Level Trends/Considerations

In developed countries, retrofits were assumed to have already been fully adopted, and in developing countries all equipment was assumed to remain nonretrofitted. In addition, although NIK replacement alternatives and HFE solvent applications currently exist worldwide, the baseline emissions considered here only cover 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, we modeled no technology adoption of the NIK and HFE solvents in the baseline.

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Foam Manufacturing Mitigation Options Considered

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 in the production of 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 ODSs (i.e., CFCs and 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.

This analysis considered the costs of reducing foam emissions by replacing HFCs with low-GWP blowing agents in various types of foam manufacturing operations. Specifically, four abatement options were identified and analyzed for reducing emissions at product/equipment production for various polyurethane (PU) and extruded polystyrene (XPS) foam products by using HC, HFO, and/or HCFO blowing agents (or blends thereof) in place of HFCs. By replacing HFCs with the identified abatement options, this analysis assumed that the total amount of high-GWP blowing agent that would have been emitted during the lifetime of the foam products produced by a facility in a given year is eliminated.

Table 5-46 summarizes the reduction efficiency assumed for each mitigation option used in the MAC analysis.

Table 5-46: Foams Manufacturing Abatement Options

Abatement Option	Reduction Efficiency	Applicability
PU commercial refrigeration foam: HFC-245fa to HCFO-1233zd(E)—EU	99%	New PU commercial refrigeration units
Low-pressure (LP), two-component PU spray foam: HFC-245fa/CO ₂ to HFO-1234ze(E)/HCFO-1233zd(E)—Developed	99%	New LP two-component spray foam products
XPS: HFC-134a/CO ₂ to HFO-1234ze(E)—EU	53%	New XPS boardstock foam products
PU OCF: HFC-134a to HCs—Developing	100%	New PU OCF applications products

HCFO-1233zd(E) in Commercial Refrigeration

This option replaces HFC-245fa used in commercial refrigeration foam with unsaturated HCFCs or HCFOs, namely HCFO-1233zd(E). HCFO-1233zd(E) has a GWP of 4.7 to 7 (EPA, 2012). Unsaturated HFCs and HCFCs with low GWPs have emerged in the market on a commercial scale as alternative blowing agents in various foam applications over the last several years.

This abatement option was applied to a facility that manufactures 50,000 units annually, with each unit containing 1.4 kilograms of blowing agent. This option is applicable to HFC-245fa in newly manufactured commercial refrigeration equipment in the EU.

- **Capital Costs:** HCFO-1233zd(E) is very similar to HFC-245fa, such that existing manufacturing equipment requires little to no change to achieve the desired operational characteristics. Therefore, no one-time costs were assumed.
- **Annual O&M Costs:** Annual costs were assumed to be a result of the incremental cost of the blowing agent replacement, which is approximately \$4/kg for HCFO-1233zd(E) relative to HFC-245fa (UNEP, 2012).
- **Annual Revenue:** No annual savings were assumed.

HFO-1234ze(E)/HCFO-1233zd(E) in Low-Pressure, Two-Component Spray Foam (Frothing Insulation and Sealant)

This abatement option applies the use of a blend of HFO-1234ze(E) and HCFO-1233zd(E) as a replacement for HFC-134a and HFC-245fa in low-pressure (LP), two-component spray foam (i.e., frothing insulation and sealant). The abatement option was assumed to be a blowing agent blend of HFO-1234ze(E) and HCFO-1233zd(E), with the same composition as the respective gaseous and liquid HFC blowing agent components assuming a 1:1 replacement ratio.

This abatement option was applied to a facility that manufactures 2.1 million pounds of LP two-component PU spray foam using HFC-134a/HFC-245fa blowing agent annually (Dow, 2018).⁷² It was assumed that the foam formulation is 17% by weight blowing agent (Dow, 2018), so the facility uses 350,000 pounds of blowing agent annually. This option is applicable to HFC-134a and HFC-245fa in newly manufactured LP two-component spray foam products in developed countries, except the EU.

- **Capital Costs:** Capital costs for transitioning to HFO-1234ze(E)/HCFO-1233zd(E) blowing agent are estimated to be up to \$2 million per facility (i.e., \$1 million for equipment modifications and \$1 million for manufacturing plant upgrades to handle flammable material [BASF, 2014; Dow, 2018]). HFO-1234ze(E) is mildly flammable, so the manufacturing plant will need to be upgraded to accommodate the use of flammable material. These upgrades include safety modifications such as new leak detection monitors, new holding tanks for raw material with containment barriers, and ventilation (BASF, 2014; Dow, 2018). Furthermore, the electrical classification must be upgraded for all equipment, such as mixing tanks, motors, light switches, and light fixtures (Dow, 2018). Costs depend on the size, layout, and existing equipment in the plant (BASF, 2014). Standard spraying equipment at end use was also assumed to be used for this abatement option (UNEP, 2008).
- **Conversion Costs:** Conversion costs include foam reformulation, product development, certifications, shelf-life studies, field and external testing, and commercialization (American Chemistry Council Center for Polyurethanes Industry [ACC CPI], 2014; BASF, 2014; Clayton Corporation, 2014; Dow, 2014; Fomo Products, 2014; RHH, 2014). Reformulation includes studying, optimizing, and testing the new foam product and requires third-party testing approvals, internal manufacturer or customer standards, the use of third-party testing, and iterative research and development (ACC CPI, 2014). New products must be tested to meet internal quality controls, dimensional stability, voluntary performance standards, and/or mandatory standards and regulations. The tests verify performance metrics such as thermal performance, fire safety, and other life and safety requirements (ACC CPI, 2014; BASF, 2014). Conversion costs are estimated to be several million dollars (BASF, 2014). For the purposes of this analysis, conversion costs were assumed to be \$3 million.
- **Annual O&M Costs:** Annual O&M costs include labor, energy, and training. Annual O&M costs for HFO-1234ze(E)/HCFO-1233zd(E) in LP two-component PU spray foam are expected to be the same as with HFC-134a/HFC-245fa. Additional training required to handle flammable material is not expected to be significantly different (i.e., may add one to two hours per employee [Dow, 2018]). Thus, the only annual incremental cost increase is due to the price differential between the blowing agents, which is approximately \$7.5/kg for HFO-1234ze(E) relative to HFC-134a and \$4/kg for HCFO-1233zd(E) relative to HFC-245fa (UNEP, 2012).
- **Annual Revenue:** Because the alternative blowing agents are more expensive on a mass basis than HFC-134a/HFC-245fa, no annual cost savings are associated with this option. Cost savings associated with the

⁷² This estimate was calculated using blowing agent consumption for the spray foam market in the United States modeled in EPA's Vintaging Model and assuming six LP two-component spray foam manufacturers in the United States, each with one facility, that comprise 10% of the total spray foam market. These six manufacturers are Dow Chemical Company, Fomo Products Inc., RHH Foam Systems Inc., Clayton Corporation, BASF Corporation, and Commercial Thermal Solutions, Inc.

increase in yield (product coverage) and R-value (insulation value) were not quantitatively accounted for in this analysis.

HFC-134a/HFO-1234ze(E) in XPS Boardstock

This abatement option applies the use of blends of HFO-1234ze(E) and HFC-134a as a replacement for HFC-134a and CO₂-based blends in extruded XPS boardstock foam. The abatement option is assumed to be a blowing agent blend of HFC-134a (42%) and HFO-1234ze(E) (58%), which is equivalent to the formulation for R-450A (i.e., a refrigerant blend currently available in the market).

This abatement option was applied to an XPS boardstock manufacturing facility that produces 100 million board feet of HFC-134a/CO₂ XPS boardstock across 1.5 lines per year (i.e., 66.7 million board feet per line [Owens Corning, 2014; Extruded Polystyrene Foam Association [XPSA], 2018]).⁷³ This option applies to all HFC-134a/CO₂ blends in newly manufactured XPS boardstock foam in the EU.

- **Capital Costs:** The capital costs for switching to HFC-134a/HFO-1234ze(E) are estimated to be \$1.8 million across 1.5 lines with up to an additional \$1 million per manufacturing plant for plant upgrades for handling flammable material (BASF, 2014; Dow, 2018). HFO-1234ze(E) is mildly flammable, so the manufacturing plant will need to be upgraded to accommodate the use of flammable material. These upgrades include safety modifications such as new leak detection monitors, new holding tanks for raw material with containment barriers, and ventilation (Dow, 2018). Furthermore, the electrical classification must be upgraded for all equipment, such as mixing tanks, motors, light switches, and light fixtures (Dow 2018). Costs depend on the size, layout, and existing equipment in the plant (BASF, 2014).⁷⁴
- **Conversion Costs:** According to XPSA, conversion costs for transitioning to a new blowing agent are required for conducting research and development to ensure the finished product can meet R-5 performance requirements per ASTM C-578 standards, pilot-scale trials, full-scale trials, certification testing, building code and fire code listing updates, emission permits, and negotiating of contracts with new suppliers (XPSA, 2014). Owens Corning spent \$132 million for the conversion from CFCs to HCFC-142b to its current HFC-134a/HFC-152a blend across six lines in four facilities in North America (Owens Corning, 2014). Assuming the conversion costs were equivalent for each blowing agent transition and incurred equally across the facilities (in the absence of more definitive information about each transition and facility), conversion costs are estimated to be \$16.5 million per facility and \$11 million per line.
- **Annual O&M Costs:** Annual O&M costs include labor, energy, and training. Total O&M costs are estimated to be \$240,000, based on an estimated cost of \$0.03 per board foot (Russell, 2005). It was assumed that blowing agent conversions would result in a 10% decrease in capacity because of slower production throughputs caused by the need for rapid expansion control for the alternative blend (Russell, 2005; XPSA, 2018). The annual incremental cost increase due to the price differential between the blowing agents is approximately \$5/kg. The goal is to have the density and thickness of the foam not change with this abatement option. Density is critical to performance properties of XPS boardstock foam, including R-value and compressive strength, which are required to meet building codes. Furthermore, XPS boardstock foam blown with an alternative blowing agent must maintain typical thickness because of the limited space requirements for building construction (Dow, 2018).
- **Annual Revenue:** Because the alternative blowing agent is more expensive on a mass basis than HFC-134a/CO₂, no annual cost savings are associated with this option.

⁷³ Owens Corning manufactures XPS boardstock across six lines in four facilities in North America (Owens Corning, 2014). According to XPSA, 100 million board feet per year is a reasonable estimate for XPS boardstock production per line (XPSA, 2018).

⁷⁴ Comments submitted by BASF are specific to facilities manufacturing PU foam but are applicable to XPS foam manufacturing given the similarities between plant upgrades needed for handling flammable material.

HCs in PU One-Component Foam (Sealant Cylinders)

This abatement option replaces HFC-134a used in PU one-component foam (OCF) (sealant cylinders) with an HC blowing agent. HCs are inexpensive and have very low direct GWPs. Technical issues exist with using HCIs, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design (EPA, 2009). A significant advantage of HCIs is that they can be easily blended to affect a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (UNEP, 2012). Flammability, however, may cause a high incremental capital cost for facilities, which may be uneconomic for small- or medium-sized enterprises; otherwise, HCIs have low operating costs (UNEP, 2012). Use of butane and propane in OCFs is well proven and is associated with low operating costs (UNEP, 2012).

This abatement option was applied to a facility that manufactures 160,000 pounds of LP PU OCF sealant cylinders across one line using HFC-134a blowing agent annually.⁷⁵ It was assumed that the foam formulation is 8.7% by weight blowing agent, so the facility uses 140,000 pounds of blowing agent annually. This option applies to all HFC-134a in newly manufactured PU OCF in developing countries.

- **Capital Costs:** Capital costs for switching to HCIs are estimated to be up to \$2 million (i.e., \$1 million per facility for equipment modifications for one line and \$1 million for facility upgrades for handling flammable material).⁷⁶ HCIs are flammable, so the manufacturing plant will need to be upgraded to accommodate the use of flammable material. These upgrades include safety modifications such as new leak detection monitors, new holding tanks for raw material with containment barriers, and ventilation (BASF, 2014; Dow, 2018). Furthermore, the electrical classification must be upgraded for all equipment, such as mixing tanks, motors, light switches, and light fixtures (Dow, 2018). Costs depend on the size, layout, and existing equipment in the plant (BASF, 2014). Standard spraying equipment at end use was also assumed to be used for this abatement option (UNEP, 2008).
- **Conversion Costs:** Conversion costs include foam reformulation, product development, certifications, shelf-life studies, field and external testing, and commercialization (ACC CPI, 2014; BASF, 2014; Clayton Corporation, 2014; Dow, 2014; Fomo Products, 2014; RHH, 2014). Reformulation includes studying, optimizing, and testing the new foam product and requires third-party testing approvals, internal manufacturer or customer standards, the use of third-party testing, and iterative research and development (ACC CPI, 2014). New products must be tested to meet internal quality controls, dimensional stability, voluntary performance standards, and/or mandatory standards and regulations. The tests verify performance metrics such as thermal performance, fire safety, and other life and safety requirements (ACC CPI, 2014; BASF, 2014). Conversion costs are estimated to be several million dollars (BASF, 2014). For the purposes of this analysis, conversion costs were assumed to be \$3 million.
- **Annual O&M Costs:** Annual O&M costs include labor, energy, and training. Annual O&M costs for switching production to HCIs from HFC-134a are estimated to be equal. Additional training required to handle flammable material is not expected to be significant (Dow, 2018). Thus, no annual O&M costs were assumed.
- **Annual Revenue:** Annual savings are estimated at about \$587,000 per facility associated with incremental blowing agent replacement costs. Cost savings associated with the increase in yield (product coverage) and R-value (insulation value) were not quantitatively accounted for in this analysis.

⁷⁵ This estimate was calculated using blowing agent consumption for the OCF market in the United States modeled in EPA's Vintaging Model and assuming six OCF manufacturers in the United States, each with one facility. These six manufacturers are Dow Chemical Company, Fomo Products Inc., RHH Foam Systems Inc., Clayton Corporation, BASF Corporation, and Commercial Thermal Solutions, Inc.

⁷⁶ Capital costs were assumed to be equivalent for any abatement option using flammable blowing agents in OCFs.

Technical and Economic Characteristics Summary

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter required developing assumptions regarding the distribution of emissions by abatement option in addition to process-specific estimates of technical applicability and market penetration. This analysis assumed that the targeted abatement amount for each abatement option in the foam sector is the total amount of high-GWP blowing agent that would have been emitted during the lifetime of the foam products produced by a facility in a given year.

Closed-cell foams are assumed to emit a portion of their total blowing agent content upon manufacture, a portion at a constant rate over the lifetime of the foam, and a portion at disposal; these portions vary by end use. The emission profiles of the foams included in this analysis are shown in Table 5-47. According to the emission profiles, 100% of the blowing agent used in each foam product is eventually emitted over its lifetime. Thus, the targeted abatement amount (i.e., emissions) for each option is equivalent to the amount of blowing agent consumed in a given year by the manufacturing facility (i.e., the total amount of blowing agent that would have been emitted from all products manufactured in that year throughout their lifetime).

Table 5-47: Emission Profiles for Foam End Uses

Foam End Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total Emissions (%)
PU commercial refrigeration units	4	0.25	15	92.25	100%
LP two-component PU spray foam	15	1.50	50	10.00	100%
XPS boardstock foam	25	0.75	25	56.25	100%
PU one-component foam	95	2.50	2	0	100%

Market penetration is a modeled value that considers 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 GHG impacts associated with changes in electricity consumption (e.g., for foam-blowing processes), which are accounted for in the cost analysis.⁷⁷ Table 5-48 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

⁷⁷ Indirect GHG emissions were 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 are available on them, are accounted for in the cost analyses.

Table 5-48: Technical Effectiveness Summary—Foams Manufacturing

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
PU Commercial Refrigeration Units—EU				
HFC-245fa to HCFO-1233zd(E)	13%	100%	99%	13%
LP Two-component PU Spray Foam—U.S./Other Developed				
HFC-245fa/CO ₂ to HFO-1234ze(E)/HCFO-1233zd(E)	52%	30%	99%	15%
XPS Boardstock Foam—EU				
HFC-134a/CO ₂ to HFO-1234ze(E)	73%	80%	53%	31%
PU OCF—Developing				
HFC-134a to HCs	95%	100%	100%	95%

^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.

^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 GHG impacts associated with increased electricity consumption (e.g., for foam blowing processes or for EOL appliance processing), which are accounted for in the cost analysis.

Table 5-49 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

Table 5-49: Engineering Cost Data on a Facility Basis—Foams Manufacturing

Abatement Option	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e)
Commercial refrigeration: HFC-245fa to HCFO-1233zd(E)					
PU commercial refrigeration foam manufacturing facility—EU	25	\$0	\$0	\$280,000	71,610
LP two-component spray: HFC-245fa/CO₂ to HFO-1234ze(E)/HCFO-1233zd(E)					
PU spray foam manufacturing facility—U.S./other developed	25	\$5,000,000	\$0	\$230,124	58,912
XPS: HFC-134a/CO₂ to HFO-1234ze(E)					
XPS boardstock production facility—EU	25	\$19,300,000	\$0	\$4,039,260	516,331
OCF: HFC-134a to HCs					
OCF manufacturing facility—Developing	25	\$5,000,000	\$587,088	\$0	185,716

Sector-Level Trends/Considerations

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).

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Aerosol Product Use Mitigation Options Considered

Aerosol propellant formulations containing HFCs are used in a variety of consumer products and 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 metered dose inhalers (MDIs). HFC-134a has been introduced as an alternative propellant to 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.

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 an NIK alternative, such as a stick, roller, or finger/trigger pump. Costs were 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 (DPI) technology where suitable for the patient. Costs were analyzed based on a single DPI compared with a single MDI, with estimated cost data that incorporate 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 patients in using the DPI (Ecofys, 2000; Enviro, 2000). Table 5-50 summarizes the applicability of each abatement option to the aerosol emission categories. The subsequent subsections describe each abatement option in more detail.

Table 5-50: Aerosol Product Use Abatement Options

Abatement Option	Reduction Efficiency			Applicability
	Consumer Aerosol Facility/ HFC-134a	Consumer Aerosol Facility/ HFC-152a	MDI	
Consumer Aerosol Products				
HC	99.7%	97.5%	NA	Consumer aerosol facility/HFC-134a/HFC-152a
NIK	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)				
DPIs	NA	NA	100%	Metered dose inhaler

For the purposes of evaluating the cost of reducing HFC emissions, this analysis characterized three categories of emission sources:

- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-134a aerosol propellant charge of 2 ounces;
- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-152a aerosol propellant charge of 2 ounces; and
- a single 200-dose MDI aerosol unit with a charge size of 15 grams that uses HFC-134a propellant.

HCs

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.⁷⁸ Their primary advantage lies in their affordability; the price of HC propellants ranges from one-third to one-half that of HFCs. The main disadvantages of HC aerosol propellants are flammability concerns and, because they are 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.

- **Capital Cost:** Costs of converting filling facilities to accept HC propellants can range from \$10,000 to potentially as high as \$1.2 million (\$325,000 was assumed); 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 (Cook, 2008; Tourigny, 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 (Cook, 2008; Tourigny, 2008).
- **Annual O&M Costs:** This analysis does not assume O&M costs.
- **Annual Revenue:** Given that HCs (estimated at \$3.50/kg) are lower cost than HFC-134a (estimated at \$8/kg) and equivalent in cost to HFC-152a (estimated at \$3.50/kg), the adoption of this abatement measure is expected to result in an annual savings associated with gas purchases, ranging from no savings to nearly \$3 million.

NIK

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%.

- **Capital Cost:** 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.
- **Annual O&M Costs:** Annual costs of \$500,000 are estimated to address higher material costs of the particular sticks, rollers, and pumps being used (UNEP, 1999).
- **Annual Revenue:** An annual savings is expected, ranging from \$2.0 million to \$4.5 million, as a result of eliminating the need for an HFC propellant.

HFO-1234ze

HFO-1234ze has potential application both as a propellant and as the active ingredient in aerosol dusters. HFO-1234ze is nonflammable (at room temperature) and has physical properties that are very similar to both HFC-134a and HFC-152a. Hence, it may be used as a “drop-in” replacement for HFC propellants (Tourigny, 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 (Malerba, 2011). A number of dusters using HFO-1234ze are available today (Amazon, 2013; ITW Chemtronics, 2013; Miller Stephenson, 2013; Stanley Supply and Services, 2013). In the absence of regulations, adoption in Europe and Japan

⁷⁸ For calculation purposes, a GWP of 3.48 was used based on an average of the GWP of propane (GWP=3.3) and isobutane (GWP=3.65).

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.

- **Capital Cost:** For this analysis, a one-time cost of roughly \$500,000 was assumed because of the need for bulk storage. According to Tourigny (2011), although it is possible to use 1-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.
- **Annual O&M Costs:** 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, ranging from \$4.3 million to \$6.8 million.
- **Annual Revenue:** No annual savings are assumed.

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 was 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.

- **Capital Cost:** Costs of converting filling facilities to accept HFC-152a may range from \$500,000 to \$600,000, (Cook, 2008; Tourigny, 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 (Cook, 2008).
- **Annual O&M Costs:** 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 (Cook, 2008; Tourigny, 2008).
- **Annual Revenue:** The lower cost of HFC-152a (compared with HFC-134a) results in an annual savings associated with gas purchases, estimated at \$2.6 million for a typical aerosol filling facility.

DPIs

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, which contains the drug agent, is contained in the DPI, a nonpressurized delivery system, and is inhaled and deposited in the lungs. DPIs 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, 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%.

- **Capital Cost:** No one-time costs are assumed.
- **Annual O&M Costs:** The annual cost associated with using DPIs was estimated to be approximately \$700,000 per metric ton of substance. This cost was based on €533,000 (in 1999 Euros) per metric ton of substance (Enviros, 2000), which translates to an annual cost of \$552,544 using the 1999 exchange rate of \$0.964629 Euros to 1 U.S. dollar. According to the source cited by Ecofys (2000), this annual cost incurred by the industry takes into account 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 (Enviros, 2000). It is unknown to what extent this value includes capital and annual costs and savings.
- **Annual Revenue:** No cost savings are assumed. A DPI treatment of 200 doses costs, on average, around \$10 more than an MDI (Enviros, 2000).

Technical and Economic Characteristics Summary

The analysis 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 5-51 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of each option.

Table 5-51: Technical Effectiveness Summary—Aerosol Products

Facility/Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
Consumer Aerosol Products—U.S. and Other Developed and EU				
HFC-134a to HC	58%	20%	100%	10%
HFC-134a to NIK	58%	20%	100%	10%
HFC-134a to HFO-1234ze	58%	20%	100%	9%
HFC-134a to HFC-152a	58%	10%	91%	5%
HFC-152a to HC	42%	20%	95%	9%
HFC-152a to NIK	42%	40%	100%	19%
HFC-152a to HFO-1234ze	42%	20%	95%	8%
Consumer Aerosol Products—Developing				
HFC-134a to HC	58%	20%	100%	10%
HFC-134a to NIK	58%	20%	100%	10%
HFC-134a to HFO-1234ze	58%	20%	100%	9%
HFC-134a to HFC-152a	58%	10%	91%	5%
HFC-152a to HC	42%	20%	95%	9%
HFC-152a to NIK	42%	40%	100%	19%
HFC-152a to HFO-1234ze	42%	20%	95%	8%
Pharmaceutical Aerosol Products (MDIs)—U.S. and Other Developed and EU				
DPIs	100%	20%	100%	20%
Pharmaceutical Aerosol Products (MDIs)—Developing				
DPIs	100%	20%	100%	20%

^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.

^b Technical effectiveness figures represent the percentage of baseline emissions from the relevant facility type that can be abated in 2030.

Table 5-52 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.

Table 5-52: Engineering Cost Data on a Facility Basis—Aerosol Products

Abatement Option	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e)
HCs					
Consumer aerosol/HFC-134a	10	\$325,000	\$2,800,000	—	807,125
Consumer aerosol/HFC-152a	10	\$325,000	\$1,000,000	—	66,623
NIK					
Consumer aerosol/HFC-134a	10	\$250,000	\$4,100,000	\$500,000	810,810
Consumer aerosol/HFC-152a	10	\$250,000	\$2,300,000	\$500,000	70,308
HFO-1234ze					
Consumer aerosol/HFC-134a	10	\$500,000	—	\$1,400,000	807,408
Consumer aerosol/HFC-152a	10	\$500,000	—	\$3,200,000	66,906
HFC-134a to HFC-152a					
Consumer aerosol/HFC-134a	19	\$500,000	\$1,800,000	—	740,502
DPIs					
Pharmaceutical Aerosols (MDI)	10	—	—	\$700,000	1,430

Sector-Level Trends/Considerations

The treatment of international variability of mitigation technology costs is a significant area of uncertainty in this analysis. The analysis is currently limited by 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.

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Fire Protection Mitigation Options Considered

The fire protection sector encompasses total flooding fire protection systems and portable (hand-held) fire extinguishers and includes emissions of HFCs and PFCs.

The alternatives to HFCs/PFCs in total flooding applications can be categorized as in-kind gaseous agent alternatives (i.e., CO₂, inert gases, fluorinated ketones) and NIK 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 NIK alternative technologies have been introduced to the market.

This analysis reviewed 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 assessed alternative agents used in newly built total flooding systems to protect against Class A surface fire hazards and newly built total flooding systems to protect against Class B fuel hazards in large (>3,000 m³) 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 were 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 facility and possibly cost-prohibitive. Portable extinguishers were not assessed because emissions from this source are small, and climate-friendly alternatives were already assumed to be used widely in the baseline.

The analyzed facilities were 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 in Table 5-53.

Table 5-53: 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%

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 5 days and a 100-year GWP of approximately 1 (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 the total flooding sector; the additional adoption of FK-5-1-12 was assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

- **Capital Cost:** Capital costs of FK-5-1-12 systems in developed countries associated with installation and equipment are estimated to be \$9.40 more than conventional HFC systems per cubic meter of protected space. Also, although the floor space requirements for this option are very similar to those of HFC

systems, there is a slight increase in the floor space needed to protect each cubic meter of space (approximately 0.0005 sq. ft.) (Wickham, 2003). Assuming an average construction cost of approximately \$176 per square foot (R.S. Means, 2007), this translates into an incremental one-time construction cost of \$0.09 per cubic meter of protected space. Therefore, the total incremental one-time cost of this option is \$9.49 per cubic meter of protected space in developed countries. Capital costs were assumed to be 10% greater in developing countries to account for higher tariffs.

- **Annual O&M Costs:** Because the additional space requirement associated with this option relative to conventional HFC systems is so small (an average of 0.0005 square feet per cubic meter of protected space [Wickham, 2003]), the additional annual costs associated with heating and cooling are also very small—less than \$0.01 annually per cubic meter of protected space. This cost was derived by multiplying the additional space requirement (0.0005 sq. ft./cubic meter of protected space) by the average electricity cost to heat/cool space, which was assumed to be roughly \$7.60 per square foot in developed countries (EIA, 2011; ICF, 2009). In developing countries, annual costs associated with electricity consumption were assumed to be 66% greater. In addition, an annual cost of \$0.09 per cubic meter of protected space was assumed to be associated with annual emissions/agent replacement costs. This cost is based on the assumption that approximately 0.74 kilograms of FK-5-1-12 agent is required to protect every cubic meter of protected space, that 2% of this amount is leaked each year, and that FK-5-1-12 has an incremental cost (relative to HFC-227ea) of approximately \$2/kg (Werner, 2011).
- **Annual Revenue:** Because the agent cost of FK-5-1-12 is greater than that of HFC-227ea, no annual cost savings were assumed for this option.

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 CO₂ 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 was 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; the additional adoption of inert gas systems was assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

- **Capital Cost:** Inert gas systems were assumed to cost \$7.13 more than conventional HFC-227ea systems in developed countries, which were estimated to cost roughly \$33 per cubic meter of protected space (average across all space sizes) (Wickham, 2003). In addition, because inert gas systems require more space to house gas cylinders than conventional HFC systems (an additional 0.023 sq. ft. per cubic meter of protected space [Wickham, 2003]), in some cases there will be additional one-time costs to construct the additional space for storage. Assuming a construction cost of about \$176 per square foot (R.S. Means, 2007), this additional space requirement translates into an incremental one-time cost of \$4.03 per cubic meter of protected space. Therefore, the total incremental capital cost of this option is \$11.16 per cubic meter of protected space. Capital costs were assumed to be 10% greater in developing countries to account for higher tariffs.
- **Annual O&M Costs:** Depending on the application, the space required to house additional gas cylinders (an additional 0.023 sq. ft. per cubic meter of protected space) will need to be heated and cooled. Based on average U.S. electricity costs of about \$7.60 per square foot (ICF, 2009; EIA, 2011), the heating and

cooling costs associated with this option result in an assumed annual cost of \$0.17 per cubic meter of protected space for developed countries. In developing countries, annual costs were assumed to be 66% greater because of higher electricity costs.

- **Annual Revenue:** Because, on average, 0.633 kilogram of HFC-227ea is needed to protect 1 cubic meter of space (Wickham, 2003) and assuming a release rate of 2% of the installed base, the emission of approximately 13 grams of HFC-227ea is avoided each year per cubic meter of protected space. Based on an average HFC-227ea cost of about \$24 per kilogram (Werner, 2011), this translates into an annual savings of \$0.30 per cubic meter of protected space. These annual savings are assumed to be the same in all regions.

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 effective in extinguishing small fires in large-volume spaces ($\geq 3,000 \text{ m}^3$) (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 (EPA, 2004).

This technology option was assumed to be applicable in large ($>3,000 \text{ m}^3$), new Class B total flooding application end uses, replacing HFCs (primarily HFC-227ea). This analysis assumed that systems designed to protect against Class B fire hazards represent an estimated 5% of the total flooding sector; the additional adoption of water mist systems was assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

- **Capital Cost:** The capital cost of water mist systems used in marine systems to protect spaces of $3,000 \text{ m}^3$ and larger in developed countries is estimated to be \$4.82 more per cubic meter of protected space than conventional HFC-227ea systems in large spaces (which are estimated to cost an average of about \$30 per cubic meter of protected space in spaces of these sizes) (Wickham, 2003).⁷⁹ In addition, because water mist systems require more space than conventional HFC systems (an additional 0.0472 sq. ft. per cubic meter of protected space [Wickham, 2003]), one-time costs associated with constructing additional space are also considered. Assuming a construction cost of roughly \$176 per square foot (R.S. Means, 2007), this additional space requirement translates into an incremental one-time cost of \$8.32 per cubic meter of protected space. Therefore, the total incremental capital cost of this option was assumed to be \$13.14 per cubic meter of protected space in developed countries. Capital costs were assumed to be 10% greater in developing countries to account for higher tariffs.
- **Annual O&M Costs:** Depending on the application, the space required to house additional gas cylinders (an additional 0.0472 sq. ft. per cubic meter of protected space) will need to be heated and cooled. Based on average U.S. electricity costs of roughly \$7.60 per square foot (ICF, 2009; EIA, 2011), the heating and cooling costs associated with this option result in an annual cost of \$0.36 per cubic meter of protected space in developed countries. In developing countries, annual costs were assumed to be 66% greater because of higher electricity costs.

⁷⁹ The cost of conventional HFC-227ea systems is less per cubic meter of protected space in large spaces than in small ones.

- Annual Revenue:** Because an average of 0.63 kilogram of HFC-227ea is needed to protect 1 cubic meter of space (for 3,000 m³ to 5,000 m³ spaces) (Wickham, 2003) and assuming a release rate of 2% of the installed base, we assumed that the emission of approximately 13 grams of HFC-227ea is avoided each year (i.e., 0.63 kilogram × 2%). Based on an average HFC-227ea cost of roughly \$24 per kilogram, this translates into an annual savings of \$0.30 per cubic meter of protected space (Werner, 2011). These annual savings were assumed to be the same in all regions.

Technical and Economic Characteristics Summary

The analysis developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/class/facility type combination. Estimating this parameter required making 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 5-54 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

Table 5-54: Technical Effectiveness Summary—Fire Protection

Facility/ Abatement Option	Technical Applicability (2030)	Market Penetration Rate (2030) ^a	Reduction Efficiency	Technical Effectiveness (2030) ^b
New Class A total flooding—U.S. and Other Developed				
FK-5-1-12	30%	35%	100%	19%
Inert gas systems	30%	19%	100%	6%
New Class A total flooding—EU				
FK-5-1-12	31%	35%	100%	20%
Inert gas systems	31%	19%	100%	6%
New Class A total flooding—Developing				
FK-5-1-12	17%	35%	100%	7%
Inert gas systems	17%	10%	100%	2%
New Class B total flooding—U.S. and Other Developed				
Water mist systems	55%	3%	100%	1%
New Class B total flooding—EU				
Water mist systems	57%	3%	100%	1%
New Class B total flooding—Developing				
Water mist systems	19%	1%	100%	0%

^a Market penetration assumptions for this analysis vary over time, and the technical effectiveness values were based on the cumulative market penetration rates assumed until that point.

^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 GHG impacts associated with increased electricity consumption for heating/cooling of additional space, which is accounted for in the cost analysis.

The analysis was based on representative project costs for model facilities in the developing and developed world, summarized in Table 5-55. 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.

Table 5-55: Engineering Cost Data on a Facility Basis—Fire Protection

Abatement Option	Project Lifetime (years)	Capital Cost (2015 USD)	Annual Revenue (2015 USD)	Annual O&M Costs (2015 USD)	Abatement Amount (tCO ₂ e)
FK-5-1-12					
New Class A total flooding—Developed	20	\$9.49	—	\$0.03	0.04
New Class A total flooding—Developing	20	\$10.44	—	\$0.03	0.04
Inert gas					
New Class A total flooding—Developed	20	\$11.16	\$0.30	\$0.17	0.04
New Class A total flooding—Developing	20	\$12.28	\$0.30	\$0.28	0.04
Water mist					
Large, new Class B total flooding—Developed	20	\$13.14	\$0.30	\$0.36	0.04
Large, new Class B total flooding—Developing	20	\$14.45	\$0.30	\$0.60	0.04

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5.2.9 HFC-23 Emissions from HCFC-22 Production

Trifluoromethane (HFC-23) is generated and emitted as a by-product during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used in emissive applications (primarily AC 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.

5.2.9.1 HFC-23 from HCFC-22 Production Emission Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for HCFC-22 production included HCFC-22 production data from UNEP (2017a); production capacity information from IHS Markit (2001), Will et al. (2004 and 2008) and Jebens et al. (2014); field data on HFC-23 emissions from Montzka et al. (2010); HFC-23 emission projections from the United States National Communications (2017); and the growth rate of feedstock HCFC-22 production from Montzka et al. (2010). In some cases, the emission estimates were reduced due to assumed market penetrations of thermal abatement technologies.

The Tier 1 basic equation to estimate HFC-23 emissions from HCFC-22 production is as follows:

$$\text{HFC} - 23 \text{ emissions} = \text{HCFC} - 22 \text{ Production} * \text{Emission Factor} \quad (5.17)$$

For HCFC-22 production, the driving factors in determining emissions are the use of process optimization and/or thermal reduction to reduce HFC-23 emissions and the projected increase in HCFC-22 production for feedstock use, which is not regulated under the Montreal Protocol.

Activity Data

Historical

Historical HCFC-22 production was estimated using an emission rate to estimate the HFC-23 emissions and subtracting any emissions that were abated through technology. The data used to estimate historical HFC-23 emissions from HCFC-22 production included:

- Country-specific HCFC production data as reported to the UNEP Ozone Secretariat (UNEP, 2017a, 2017b);
- 2001, 2004, 2007, and 2013 country-specific production capacity information from the *Chemical and Economics Handbook* (IHS Markit, 2001; Will et al., 2004; Will et al., 2008; Jebens et al., 2014); and
- Field data on HFC-23 emissions from HCFC-22 production (Montzka et al., 2010).

Estimating Production in Europe

Information on historical HCFC-22 production was used to estimate HFC-23 emissions. According to Jebens et al. (2014), HCFC production from Greece, the Netherlands, and Spain is only HCFC-22 (based on plant capacities). UNEP (2017a) reports total nonfeedstock HCFC production by country in ODP-weighted tons. As a result, nonfeedstock HCFC-22 production for these countries was assumed to be the total reported for each country in UNEP (2017a) after “unweighting” the production estimates by HCFC-22’s ODP of 0.055. The ratio of nonfeedstock production to feedstock production was then used to estimate nonfeedstock HCFC-22 production to total HCFC-22 production, without exceeding the production capacities reported in the *Chemical and Economics Handbook* (IHS Markit, 2001; Will et al., 2004; Jebens et al., 2014). The ratio of nonfeedstock production to feedstock production,

as shown in Table 5-56, was estimated over the time series based on data for 1990 from EPA (2006) and data for 1996 and 2007 from Montzka et al. (2010) and by linearly interpolating the intervening years. The ratio of nonfeedstock production to feedstock production from 2008 through 2015 was assumed to be equal to the 2007 estimate from Montzka et al. (2010).

Table 5-56: Portion of Total HCFC-22 Production That is Feedstock HCFC-22

Production for A1 Countries

1990	1995	2001	2002	2003	2004	2005	2006	2007–2015
20%	26%	41%	44%	47%	50%	52%	55%	58%

This total was subtracted from western Europe production from Jebens et al. (2014) across the time series, and the remaining HCFC-22 production for western Europe is allocated to France, Germany, Italy, and the U.K. based on total HCFC-22 production capacity for each country as reported in *Chemical and Economics Handbook* (IHS Markit, 2001; Will et al., 2008; Will et al., 2004; Jebens et al., 2014). For all European countries, it was assumed that production from 1990 through 2003 could not exceed 2001-reported capacity, production in 2004 through 2006 could not exceed 2004-reported capacity, and production in 2007 through 2015 could not exceed 2013-reported capacity.

Estimating Production in the Rest of the World

Based on plant capacities from Will et al. (2004), HCFC production in Mexico, Argentina, Venezuela, and India was also only HCFC-22. Again, UNEP (2017a)-reported HCFC production was assumed to be the total nonfeedstock HCFC-22 production reported for each country by “unweighting” the production estimates by dividing the total production by HCFC-22’s ODP of 0.055.

For South Korea, 33% of total HCFC production capacity was HCFC-22 (Will et al., 2004, 2008; Jebens et al., 2014). This percentage was applied across the UNEP-reported nonfeedstock HCFC production time series to estimate nonfeedstock HCFC-22 production totals. The ratio of nonfeedstock production to feedstock production was then used to estimate nonfeedstock HCFC-22 production to total HCFC-22 production. For North Korea, UNEP (2017a) provided HCFC-22 production estimates for 2007 through 2015.

Jebens et al. (2014) reported China’s HCFC-22 production for 2003 through 2013. HCFC-22 production was back casted using the ratio of total HCFC-22 production reported in Jebens et al. (2014) to UNEP-reported nonfeedstock HCFC production for 2003. This ratio was applied across the UNEP-reported time series for 1990 to 2002 and 2014 to estimate China’s HCFC-22 production for those years. UNEP (2017b) reported HCFC-22 production in China for 2015. The ratio of nonfeedstock production to feedstock production across the time series for China and other Non-A1 countries and Russia is shown in Table 5-57.

Table 5-57: Portion of Total HCFC-22 Production That is Feedstock HCFC-22 Production for Non-A1 Countries

Countries	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007–2015
Non-A1	20%	31%	29%	28%	27%	26%	26%	25%	24%	23%
China	44%	55%	53%	52%	51%	50%	49%	48%	47%	46%

Projected

HFC-23 emission projections were developed for A1 countries including Germany, Japan, the Netherlands, Russia, Spain, and the United States. For the United States, national communications projections of emissions were

used for 2015 through 2020 (UNFCCC, 2017a). Emission trends were used to project HFC-23 emissions for the remainder of the time series (2025 through 2050).

For all other A1 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 phase-out requirements of the Montreal Protocol. The following assumptions for these countries were applied to estimate dispersive production:

- UNFCCC reported zero emissions of HFC-23 for Australia and Canada, beginning in 2000 and 1995, respectively (UNFCCC, 2017b). No further data were available on Australia, so the EPA assumed Australia will not produce HCFC-22 in the future. Jebens et al. (2014) reports that Canada only produces one HCFC, HCFC-123, so it was assumed that Canada will not produce HCFC-22 in the future.
- For Greece and the U.K., HCFC-22 production was assumed to end due to plant closures in 2006 and 2008, respectively, and therefore emissions were set equal to zero. For Spain, HCFC production has not been reported to UNEP since 2011, so it was assumed that nonfeedstock production of HCFC-22 ended.
- For developed countries other than Australia, Canada, the U.K., and Spain, emissions from nonfeedstock production were assumed to decrease linearly from 2015 so that no emissions resulted from HCFC-22 nonfeedstock production by the 2020 phase-out date under the Montreal Protocol.

To project the feedstock production portion of HFC-23 emissions for developed countries, a 5% global growth rate of feedstock HCFC-22 production as reported in Montzka et al. (2010) was applied for all countries.

HFC-23 emission projections were developed for Non-A1 countries including Argentina, China, India, Mexico, North Korea, South Korea, and Venezuela. To do so, Non-A1 aggregate HCFC-22 production was projected for both dispersive and feedstock production.

- **HCFC-22 dispersive production** for developing countries was projected using a 2010 HCFC-22 production estimate of 395,000 metric tons, as provided by Miller and Kuijpers (2011), and a baseline estimate of 383,000 metric tons and the percentage reductions from that baseline as prescribed by the accelerated phase-out schedule of the Montreal Protocol.
- **HCFC-22 feedstock production** was projected for developing countries based on the 5% global growth rate of feedstock HCFC-22 production, as reported in Montzka et al. (2010).

Production was then disaggregated by country using the percentage of each country's contribution to 2015 Non-A1 total HCFC-22 production.

Each country's HCFC-22 projected production was then apportioned into four different model facilities for each developing country. The model facilities for which HCFC-22 production projections were apportioned are as follows:

- **Residual emissions:** These facilities already have abatement controls in place. Facilities that have CDM projects (mitigation projects funded by developed countries under the Kyoto Protocol) in developing countries are considered "residual emission facilities." In addition, China implemented 15 destruction facilities not covered by CDM that are considered "residual emission facilities" (UNEP, 2017b).
- **Non-CDM and uncontrolled facility:** Non-CDM facilities are existing facilities that are uncontrolled. These facilities exist in China, Venezuela, Mexico, and North Korea (UNEP, 2017b).
- **New uncontrolled facility:** New facilities were assumed to be uncontrolled when built. It was 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 zero until projected production exceeds capacity.
- **Post-CDM facility:** These are facilities that were previously controlled under the CDM ("residual emission model facility"). It was assumed that the incineration device installed (via a CDM project) is not kept in

operation. In 2013, the EU Emissions Trading System, New Zealand, and Australia imposed a ban on the use of Certified Emission Reduction credits from HFC-23 destruction, which significantly lowered the value of credits obtained from HFC-23 abatement projects. Signed in 2016, the Paris Agreement universally rejects HFC-23 projects for offset credits. Several facilities with CDM projects are no longer destroying HFC-23 emissions without the generation of these credits. Post-CDM facilities exist in Argentina, Mexico, India, and South Korea.

Emission Factors

Historical and Projected

To estimate emissions of HFC-23, the estimated HCFC-22 production levels were multiplied by emission rates (i.e., tons of HFC-23 emitted per ton of HCFC-22 produced). The emission rate for A1 countries was assumed to be 2% across the entire time series (Montzka et al., 2010).

To address the varying use of abatement technologies by facilities, HFC-23 emissions for developing countries were then projected using two HFC-23/HCFC-22 co-production ratios to develop estimates. The HFC-23/HCFC-22 co-production ratio of 2.9%, representative of the CDM's annual mean ratio for 2009, was used to estimate emissions (Miller et al., 2010). For emissions associated with the “residual” model facility, the HFC-23/HCFC-22 co-production ratio was modified by 95% to account for a reduction in efficiency associated with the incinerator.⁸⁰

Emission Reductions in Baseline Scenario

In some cases, the emission estimates were reduced due to assumed market penetrations of thermal abatement technologies. The emission rate for Non-A1 countries and Russia was assumed to be 3% from 1990 through 2005 (EPA, 2006) and 2.4% from 2006 through 2015 (Miller et al., 2010). The decreased emission rate takes into account any HFC-23 emission offsets from CDM projects in these countries and the Joint Implementation project at Russia’s HCFC-22 plant in Perm.

To reflect the adoption of thermal oxidation technology between 1995 and 2015, we reduced current emission rates relative to historical emission rates in some regions. The following market penetrations were incorporated into the analysis:

- In 2000, the baseline market penetration of thermal oxidation was estimated to be 100% in Germany, France, and Italy and 75% in the U.K. (Harnisch and Hendriks, 2000). Except for the U.K., these levels were assumed to be maintained through 2050.
- In 2005, the baseline market penetration of thermal oxidation in the U.K. was estimated to be 87.5%. This was intended to reflect the 2005 commissioning of a thermal oxidizer at the one U.K. plant that had not had one previously (Campbell, 2006). For 2006 through 2008, the level of baseline market penetration in the U.K. was estimated to be 100%. No emissions were estimated for the U.K. after 2008 as a result of two HCFC-22 plants closings in 2008 (MacCarthy et al., 2010).
- In 2005, the baseline market penetration of thermal oxidation in the Netherlands was assumed to be 100%.

Uncertainty

In developing these emission estimates, the EPA made use of multiple international datasets, country-specific information on abatement levels (where available), and the 2006 *IPCC Guidelines* on estimating emissions from this source. Nevertheless, uncertainties exist in both the activity data and the emission rates used to generate these emission estimates. Although the EPA used four separate sources to estimate country-by-country production of HCFC-22 (UNEP-reported, country-specific HCFC production, country-by-country production capacities from the

⁸⁰ The assumption of 95% destruction efficiency is conservative. Although reduction efficiency is closer to 99.99% for incineration, a lower reduction efficiency takes into account startups, shutdowns (e.g., for cleaning), and malfunctions.

Chemical and Economics Handbook; and field data on HFC-23 emissions from HCFC-22 production), none of these sources is comprehensive. Specifically, none provides country-by-country production of HCFC-22 for all countries. As a result, the EPA used different ratios to estimate total HCFC-22 production over time for several countries (e.g., percentage of total HCFC production capacity that is HCFC-22 for South Korea). These ratios may add uncertainty to the extent that the ratios fluctuate over time.

Future emission and abatement levels are particularly uncertain. Future policies (e.g., under the Montreal Protocol) could affect total production of HCFC-22 and therefore emissions of HFC-23. For example, the Kigali Amendment to the Montreal Protocol mandates all HCFC-22-producing facilities to collect and destroy HFC-23 by-products from 2020 to the extent practicable. Because most, if not all, HCFC-22 production plants have access to existing destruction facilities, they could restart the equipment that was used to destroy HFC-23 previously if the equipment is not currently in use. Changing emission rates may also have a significant impact on emissions. There is a significant probability that many of these emissions will be averted. In this case, HFC-23 emissions would be lower than projected in this analysis.

5.2.9.2 Mitigation Options Considered for HCFC-22 Production

One abatement option, thermal oxidation, was examined in this analysis of the HCFC-22 production sector. Thermal oxidation, the process of oxidizing HFC-23 to CO₂, hydrogen fluoride (HF), 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 operating. Units may experience some downtime because of the extreme corrosivity of HF and the high temperatures required for complete destruction. This analysis assumed a reduction efficiency of 95%.⁸¹ The destruction of HFC-23 by thermal oxidation was assumed to be 100% applicable to all facilities, and the analysis assumed a project lifetime of 20 years. Cost estimates for installing and operating a thermal oxidizer are summarized below:⁸²

- **Capital Cost:** The capital cost for a thermal oxidation system is estimated to be approximately \$5.2 million to install at an existing plant and \$4.0 million to install during construction of a new plant (Irrgang, 2018). The capital cost for restarting an existing incinerator is estimated to be approximately \$400,000 (Irrgang, 2018 and UNEP, 2017b).
- **Annual O&M Costs:** O&M costs are estimated at \$200,000 (Irrgang, 2018).
- **Annual Revenue:** No annual savings or revenues are associated with the thermal oxidation abatement option.⁸³
- **Technical Lifetime:** 20 years
- **Reduction Efficiency:** Thermal oxidation technology was assumed to be 95% efficient in abating HFC-23 emissions.

⁸¹ 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).

⁸² 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.

⁸³ It should be noted that annual revenue is generated for participants of CDM projects; however, CDM projects were not assumed to cover further abatement of emissions in this analysis.

5.2.9.3 Model Facilities

This analysis developed four potential model facilities to model the mitigation potential in this sector. These facilities included the following:

- **Residual emissions:** These facilities have abatement controls in place already. All facilities in the A1 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 were assumed to be uncontrolled when built. It was 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 was assumed that new facilities will only be built in Non-A1 countries.
- **Post-CDM facility:** Similar to the “less mitigation scenario” of Miller and Kuijpers (2011), this analysis assumed 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). Under this assumption, by 2020, all facilities previously controlled via CDM (“residual emission model facility”) are considered a “post-CDM” facility. It was 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 considering capital costs associated with restarting the incinerator.

5.2.9.4 Technical and Economic Characteristics Summary

The analysis 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 5-58 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of thermal oxidation for each facility type.

Table 5-58: Technical Effectiveness Summary—HCFC-22 Production

Model Facility Type	Technical Applicability	Market Penetration Rate	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%

5.2.9.5 Sector-Level Trends/Considerations

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 due to the CDM project, the costs to adopt the abatement measure relate only to its annual operation. Facilities participating in CDM were assumed to have completed their crediting periods by 2020.

This analysis also assumed that new facilities will enter the market to meet future global demand of HCFC-22. New facilities were assumed to enter the market once projected production for a Non-A1 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 analysis used a capital cost for new facilities that is approximately 23% less than the cost of installation at existing facilities (Irrgang, 2018).

5.2.9.6 References

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5.2.10 Other Industrial Processes

- Other industrial processes sources (CH_4 , N_2O), include
 - chemical production (CH_4)
 - iron and steel production (CH_4)
 - metal production (CH_4 , N_2O)
 - mineral products (CH_4)
 - petrochemical production (CH_4)
 - silicon carbide production (CH_4)
 - solvent and other product use (N_2O)

5.2.10.1 Other Industrial Processes Projections Methodology

The source category solely comprises countries that report data to the UNFCCC database. The EPA did not perform Tier 1 calculations for other industrial process sources, which include the production of mineral products, ammonia, silicon carbide, calcium carbide, iron and steel, ferroalloys, and solvent and other product use. The EPA obtained historical values for 1990 through 2012 and held 2015 through 2050 values constant at 2012 levels for each country.

5.2.10.2 Other Industrial Processes Mitigation Methodology

The EPA has not estimated mitigation potential from other industrial processes because of a lack of available data on mitigation options.

5.3 Agricultural Sector

This section presents the methodology for estimating global CH₄ and N₂O emissions and mitigation for the following agricultural sources:

- enteric fermentation (CH₄)
- manure management (CH₄, N₂O)
- cropland soils (N₂O)
- rice cultivation (CH₄)

The baseline projections also include other agricultural sources, including

- field burning of agricultural residues (CH₄, N₂O) and
- prescribed burning of savannas (CH₄, N₂O).

Mitigation options are only developed and applied to the first four categories, which account for most agricultural sector non-CO₂ GHG emissions. Additional details are described below.

5.3.1 Livestock Management

Livestock operations generate CH₄ and N₂O emissions. The GHG emissions mainly come from two sources: enteric fermentation and manure management. Enteric fermentation refers to a process whereby microbes in an animal's digestive system break down cellulose, and CH₄ is produced as a by-product and can be exhaled by the animal. Domesticated ruminants such as cattle, buffalo, sheep, goats, and camels account for the majority of enteric fermentation CH₄ emissions. Other domesticated nonruminants such as swine and horses also produce CH₄ as a by-product of enteric fermentation, but emissions per animal species vary significantly.

Global livestock inventories typically include cattle, buffalo, sheep, goats, camels, horses, mules, asses, deer, alpaca, poultry, and swine. Our mitigation analysis, however, is restricted to the animal types for which mitigation (and mitigation estimates) is most feasible, including enteric fermentation and manure management for cattle and manure management for swine. Enteric fermentation calculations are described first. In the next section, we describe the methodology for calculating baseline emissions of CH₄ from all animal types. We then describe the methodology for calculating mitigation potential for cattle.

5.3.1.1 Enteric Fermentation Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for enteric fermentation included animal population data from FAO (2016) and livestock product growth rates from IFPRI's IMPACT model (2016).

The Tier 1 basic equation to estimate CH₄ emissions from enteric fermentation from each individual type of animal is as follows:

$$\text{Emission Factor (kg/head/yr)} \times \text{Animal Population (head)} / (10^6 \text{ kg/Gg}) = \text{Emissions (Gg/yr)} \quad (5.18)$$

The primary driver for determining CH₄ emissions from enteric fermentation was animal population. It was assumed that the animal characteristics on which the default emission factors are based do not change significantly over time.⁸⁴ Emissions from enteric fermentation were broken out by livestock type.

Activity Data

Historical

- Animal population data for years 1990, 1995, 2000, and 2005 through 2014 were obtained from FAO (2016). Populations of nondairy cattle were calculated by subtracting FAO dairy cattle populations from FAO total cattle populations.⁸⁵
- If reported emissions were available only for a portion of the time series, emissions were interpolated using the available data in conjunction with the growth rate associated with the estimated Tier 1 emissions calculated for the country.
- The FAO population data were further modified in instances where country data were aggregated for part of the time series. For example, in 1990, animal population data were not available for certain countries that were formed after the dissolution of the FSU. Therefore, for each region, the percentage contribution of each country to its regional total was determined using animal population data for subsequent years with available data. These percentages were then applied to fill in gaps in animal populations for these countries.

Projected

- Emissions from 2015 through 2050 were projected based on livestock product growth rates developed by the IFPRI's IMPACT model (Robinson et al., 2015; Sulser et al., 2015).⁸⁶ The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, and milk for the years 2015 through 2050 in 5-year increments. These estimates were used to proxy average annual growth rates for the livestock species, nondairy cattle, swine, sheep, and dairy cattle, respectively. For the remaining livestock types, the average population growth rates from 2005 through 2014 in the FAO data were applied.⁸⁷
- The growth rates described above were applied to the 2014 FAO animal populations to calculate projected populations for 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050 for each livestock species.

Emission Factors

Historical and Projected

- Tier 1 default emission factors from the *2006 IPCC Guidelines* were used in the calculated emissions (IPCC, 2006).

⁸⁴These projections do not take into account changes in CH₄ emissions due to variations in feed composition, feed intake, or improved animal genetics, all of which could increase or decrease CH₄ emissions compared to the Tier 1 emission factors (Rojas-Downing et al., 2017).

⁸⁵FAO animal population data are based on total meat production (from both commercial and farm slaughter) and milk production for a given year and do not take into account fluctuations in animal populations due to seasonal births or slaughter. FAO data on livestock numbers are intended to cover all domestic animals irrespective of their age and the place or purpose of their breeding and, as such, do not distinguish between slaughtered dairy or beef cattle.

⁸⁶The IMPACT model incorporates supply and demand parameters to determine the estimated growth rates. These parameters include the feed mix applied according to relative price movements, international trade, national income, population, and urban growth rates, as well as anticipated changes in these rates over time.

⁸⁷Basing livestock population growth on the 2005 through 2014 historical trend led to unrealistically high growth rates in some countries that have experienced large livestock increases in recent years. In countries where the growth between 2014 and 2050 was greater than 200%, the trend was adjusted to draw on a longer historical period. When possible, the period used was 1990 through 2014; however, in some cases, a shorter period was necessary to keep growth as close as possible to the range considered reasonable (i.e., 200% or less).

- For buffalo, sheep, goats, camels, horses, mules and asses, deer, alpacas, and swine, the appropriate enteric fermentation emission factors for either “developed” or “developing” countries were used. For dairy and nondairy cattle, enteric fermentation emission factors for world regions were used with factors assigned to countries based on the region in which they are located.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

The greatest uncertainty of emissions from enteric fermentation is associated with the use of default IPCC emission factors because of the lack of information on country-specific animal diets. Emission estimates for countries with a variety of animal diets could be inaccurate, particularly when projecting emissions, because there is a lack of information on potential changes in the quality, quantity, and type of feed that could affect projected emissions in future years. Additionally, the emission projections do not take into account improved animal genetics that could reduce emissions in enteric fermentation (Rojas-Downing et al., 2017). There are also uncertainties associated with the animal population data. FAO data are derived from country, self-reported amounts of animals slaughtered within national boundaries or milk produced (or estimated values if countries do not self-report). Animal population data are based on total annual meat (from both commercial and farm slaughter) and milk production for a given country and do not take into account fluctuations in animal populations due to seasonal births or slaughter (FAO, 2016). Additionally, FAO data cover all domestic animals irrespective of their age and the place or purpose of their breeding and, as such, do not distinguish between slaughtered dairy or beef cattle, which have different emission factors. Finally, the impacts of either historical population trends or world markets and consumption patterns on national livestock production patterns are often difficult to predict, further increasing the uncertainty of projected emissions from this source.

5.3.1.2 Mitigation Options Considered for Enteric Fermentation

This section characterizes the mitigation technologies that can be applied to reduce enteric CH₄ emissions. 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, 2008a; Whittle et al., 2013). However, developing consistent and region-specific cost estimates for emerging mitigation measures or options that are not widely adopted is a challenging task. The measure performance and cost data are scarce and often reflect anecdotal experience reported in a specific country, region, or livestock production system.⁸⁸

Based on the availability and quality of mitigation measure cost and emission reduction efficiency information, this analysis evaluated six mitigation options for enteric fermentation CH₄ emissions (Table 5-59). Each technology is briefly characterized followed by a discussion of the abatement measures’ implementation costs, potential benefits, and system design assumptions used in the MAC analysis. Many of the currently available enteric fermentation mitigation options 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

⁸⁸ In addition, although there are potential opportunities for mitigation from dietary shifts relative to the baseline (Popp et al., 2010), our assessment focuses on technical mitigation options within the agricultural sector rather than structural or demand adjustments (see Frank et al. [2018] for a study that incorporates all three within a market modeling framework).

milk, and fewer animals mean reduced GHGs (e.g., there is a reduction in GHG intensity for production of livestock products).⁸⁹

- **Improved Feed Conversion:** Improved feed conversion 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.
- **Antibiotics:** Antibiotics (e.g., monensin) may be fed to cattle to promote increased weight gain and reduce feed intake per metric ton of meat produced.
- **Bovine Somatotropin (bST):** bST may be administered 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 where the use of bST is currently expected to be legal and feasible.
- **Propionate Precursors:** Propionate precursors (malate, fumarate) may be administered to animals daily. Hydrogen produced in the rumen through fermentation can react to produce either CH₄ or propionate. By adding propionate precursors to animal feed, more hydrogen is used to produce propionate and less CH₄ is produced.
- **Antimethanogen:** Antimethanogen is a vaccine that can be administered to animals to suppress CH₄ production in the rumen. The vaccine is currently in infancy of development with limited information on emission reduction efficiency, long-term mitigation effects, and animal health impacts.
- **Intensive Grazing:** Intensive grazing means improving nutrition through more intensive pasture management and cattle rotations to allow for regrowth while decreasing reliance on prepared rations.

5.3.1.3 Technical and Economic Characteristics of Options

Table 5-59 provides descriptions of the technical and economic characteristics of the abatement measures for enteric fermentation included in this analysis. For all enteric mitigation options considered, we assumed no initial capital costs. Recurring annual costs range from -\$180 to \$300 per head of livestock. Negative costs indicate cost savings in this table such as reductions in feeding operations costs.

Table 5-59: Abatement Measures for Enteric Fermentation CH₄

Abatement Option	Total Installed Capital Cost (2010 USD)	Annual O&M Cost (2010 USD)	Lifetime Capital (years)	Reduction Efficiency (change in emissions per head)	Benefits (changes in livestock or energy revenue)	Technical Applicability
Improved feed conversion	0	\$25–\$295 per head	NA	CH ₄ : -39.4% to +39.6%	0–79% increase in animal yield	Beef and dairy cattle in areas with low baseline livestock growth and milk production rates
Antibiotics	0	\$4–\$9 per head	NA	CH ₄ : -0.4% to -6%	5% increase in animal yield	Beef cattle in urban and intensively managed livestock production systems (LPS)
bST	0	\$123–\$300 per head	NA	CH ₄ : -0.2% to +10.3%	12.5% increase in animal yield	Dairy cattle in urban and intensively managed LPS within countries where bST is currently expected to be legal and feasible

(continued)

⁸⁹ There are a variety of additional mitigation options under development that may be incorporated in future analyses as sufficient data become available (e.g., wide array of different changes to livestock feed, additional supplements, breeding programs).

Table 5-59: Abatement Measures for Enteric Fermentation CH₄ (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
Propionate precursors	0	\$40–\$120 per head	NA	CH ₄ : -10% beef cattle and sheep; -25% dairy animals	5% increase in animal yield	Beef cattle, sheep, and dairy animals in urban and intensively managed LPS
Anti-methanogen	0	\$9–\$33 per head	NA	CH ₄ : -10%	5% increase in animal yield	All ruminants in urban and intensively managed LPS
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	Beef and dairy cattle in developed regions and Latin America in urban and intensively managed LPS

Note: Annual costs and reduction efficiencies were calculated for each region based on Gerbens (1998), Bates (2001), and professional judgment based on consultations with experts.

5.3.1.4 Manure Projections Methodology

When available, UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for manure management included animal population data from FAO (2016) and livestock product growth rates from IFPRI's IMPACT model (2016).

The Tier 1 basic equation to estimate CH₄ emissions from manure management is as follows:

$$\text{Emission Factor (kg/head/yr)} \times \text{Animal Population (head)} / (10^6 \text{ kg/Gg}) = \text{Emissions (Gg/yr)} \quad (5.19)$$

The primary driver for determining CH₄ emissions from manure management is animal population, assuming that waste management and animal characteristics do not change significantly over time.⁹⁰ Within manure management, emissions were broken out by gas and livestock type.

Activity Data

Historical

- Animal population data for 1990, 1995, 2000, and 2005 through 2014 were obtained from FAO (2016). Populations of nondairy cattle were calculated by subtracting FAO dairy cattle populations from FAO total cattle populations.⁹¹

⁹⁰ These projections do not take into account changes in manure production or composition due to variations in feed composition, feed intake, or improved animal genetics, nor do they include potential changes to future waste management practices, all of which could increase or decrease methane emissions compared to the Tier 1 emission factors (Rojas-Downing et al., 2017).

⁹¹ FAO animal population data are based on total meat production (from both commercial and farm slaughter) and milk production for a given year and do not take into account fluctuations in animal populations due to seasonal births or slaughter. FAO data on livestock numbers are intended to cover all domestic animals irrespective of their age and the place or purpose of their breeding and, as such, do not distinguish between slaughtered dairy or beef cattle.

- If country-reported emissions were available only for a portion of the time series, emissions were interpolated using the available data in conjunction with the growth rate associated with the estimated Tier 1 emissions calculated for the country.
- The FAO population data were further modified in instances where country-reported data were aggregated for part of the time series. For example, in 1990, animal population data were not available for certain countries that were formed after the breakup of the FSU (Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan), Yugoslavia (Bosnia, Croatia, Macedonia, Slovenia, and Serbia and Montenegro), Czechoslovakia (Czech Republic and Slovakia), and Ethiopia (Ethiopia and Eritrea). In addition, animal population data from Belgium and Luxembourg were reported jointly until 2000, and animal population data from Serbia and Montenegro continued to be reported together until 2006. Therefore, for each region, the EPA determined the percentage contribution of each country to its regional total using 1995 (1993 for Czechoslovakia), 2000, or 2006 animal population data. The EPA then applied these percentages to estimate 1990, 1995, 2000, and/or 2005 animal populations for these countries.
- Default manure management system usage values were taken from the IPCC (2006) Guidelines, Tables 10A-4 to 10A-9, except from poultry emission factors, which were taken from the IPCC (1996) methodology employed in the 2006 EPA-published report (EPA, 2006).

Projected

- Country-reported emission estimates for 2010, 2015, 2020, 2025, and 2030, if available, were used. If country-reported emission projections were not available, the EPA projected emissions from 2005 through 2050 based on livestock product growth rates developed by the International Food Policy Research Institute's IMPACT model (IFPRI, 2016; Robinson et al., 2015; Sulser et al., 2015).⁹² The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, poultry, and milk for the years 2005 through 2050 in 5-year increments. These estimates were used to proxy average annual growth rates for the livestock species, nondairy cattle, swine, sheep, all poultry (including turkeys, ducks, geese, and chickens) and dairy cattle, respectively. For the remaining livestock types, the average population growth rates from 2005 through 2014 in the FAO data were applied.⁹³
- The growth rates described above were applied to the 2014 FAO animal populations to calculate projected populations for 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050 for each livestock species.

Emission Factors

Historical and Projected

- For sheep, goats, camels and other camelids, horses, mules and asses, and poultry, CH₄ emission factors for both developed and developing countries were obtained from the 2006 IPCC Guidelines (IPCC, 2006) by climate type (i.e., cool, temperate, or warm).

⁹² The IFPRI IMPACT model incorporates supply and demand parameters to determine the estimated growth rates. These parameters include the feed mix applied according to relative price movements, international trade, national income, population, and urban growth rates, as well as anticipated changes in these rates over time.

⁹³ Basing livestock population growth on the 2005 through 2014 historical trend led to unrealistically high growth rates in some countries that have experienced large livestock increases in recent years. In countries where the growth between 2014 and 2050 was greater than 200%, the trend was adjusted to draw on a longer historical period. Where possible, the period used was 1990 through 2014; however, in some cases, a shorter period was necessary to keep growth as close as possible to the range considered reasonable (i.e., 200% or less).

- For cattle, swine, and buffalo, CH₄ emission factors from the 2006 IPCC Guidelines were used and were selected based on region and average annual temperature (provided in increments of 1° Celsius) for the country.
- According to IPCC (2006) Tier 1 default assumptions, N₂O from manure for animal categories other than cattle, buffalo, swine, and poultry was assumed to be managed in pasture and grazing operations and was therefore not included in the manure management estimates. Therefore, manure management emissions from these animal types were assumed to be zero and were estimated under N₂O from agriculturally managed soils.
- For cattle, buffalo, swine, and poultry, all default data for determining N₂O emission factors were obtained from the 2006 IPCC Guidelines (IPCC, 2006). Nitrogen excretion rates (kilograms nitrogen per 1,000 kg animal mass) were obtained by animal type and region and were used in conjunction with typical animal mass estimates (in kilograms, available by animal type and region for cattle, swine, and buffalo and by developed or developing country designation for poultry) to calculate a nitrogen excretion rate per head per year for each animal type and region and also by developed or developing country designation for poultry. The nitrogen excretion rate was used with default manure management system usage estimates and the associated emission factors for each management system to calculate default emission factors per head per year by animal type and region for cattle, buffalo, and swine and by region and developed or developing country designation for poultry. Climate type for most countries was identified using data from the Global Historical Climatology Network, which are published by the National Climatic Data Center and contain annual average temperatures for most countries' capitals or major cities. These annual averages are for a range of years, which vary by country. Given the lack of animal population data by areas within a country, it was assumed that 100% of the animal populations are located in a climate defined by the average temperature of the country capital. When climate data were not available for a specific country, either a nearby country was used as a proxy or the general climate type (warm, temperate, cool) was taken from a previous manure CH₄ model from 2002 and the median temperature for that climate type was used.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

The default IPCC emission factors represent the greatest source of uncertainty because of the lack of information on country-specific manure management systems and the geographic concentration of animal populations, which affects the climate zone assignment. Considerable uncertainty in projected emissions is due to the lack of information on potential changes to management system types and animal feeding characteristics that could affect emissions in the projected years. Additionally, the emission projections do not take into account improved animal genetics that can reduce emissions in enteric fermentation, nor do they take into consideration future potential changes to manure management practices (Rojas-Downing et al., 2017). There are also uncertainties associated with the animal population data. FAO data are derived from total annual meat (from both commercial and farm slaughter) and milk production data for a given country and do not take into account fluctuations in animal populations due to seasonal births or slaughter. (FAO, 2016). Additionally, the impacts of either historical population trends or world markets and livestock product consumption patterns on national livestock production patterns are often difficult to predict, further increasing the uncertainty of projected emissions from this source.

5.3.1.5 Mitigation Options Considered for Manure

Mitigation options for reducing CH₄ from livestock manure focus on changes in manure management practices that capture the CH₄ to flare or use for energy production (see Table 5-60). This analysis included 10 options for manure management of CH₄ emissions including both large capital-intensive digesters applied in developed regions and small-scale digesters for developing regions. Revenues were generated from using captured CH₄ for either heat or electricity on the farm; these revenues were scaled to other regions based on an electricity price index. Capital costs and O&M costs for digester systems were mainly based on the EPA AgSTAR program data and experience in the United States and developing countries (EPA, 2010; Roos, personal communication 2012; Costa, personal communication 2012), supplemented by information from USDA (2007, 2011). For the EU, technology cost and performance parameters were based on Bates et al. (2009). For developing countries, the U.S. technology cost data were assumed for large digester systems with adjustments made to represent O&M costs in the developing countries. Capital costs for small-scale systems were based on EPA (2006), which estimates the capital cost per 1,000 pounds live weight.⁹⁴

- **Complete-Mix Digesters:** Complete-mix 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 the manure accumulates in a mixing tank before entering the digester. These digesters make use of gravity and pumps to move the manure through the system. These digesters are typically heated to maintain a constant temperature and gas flow.
- **Plug-Flow Digesters:** Plug-flow 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%.
- **Fixed-Film Digesters:** Fixed-film digesters may be appropriate when 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.
- **Covered Lagoons:** Covered earthen lagoons are the simplest of the systems used in developed countries and generally the least expensive, although 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. CH₄ 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.
- **Dome Digesters:** 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.
- **Centralized Digesters:** Centralized digesters are large digesters to which individual farmers transport their waste for large-scale digestion and dispersion of capital costs.

5.3.1.6 Technical and Economic Characteristics of Options

Table 5-60 provides a description of the technical and economic characteristics of the abatement measures for manure management included in this analysis.

⁹⁴ Additional strategies that may be considered in future assessments include the addition of manure separation prior to anaerobic digestion and other changes in the way that manure is captured and stored.

Table 5-60: 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	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	790 per head (US)	8.9	20	CH ₄ : -85%	None	Dairy cattle in selected LPS and management intensities	Labor costs, labor share
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

(continued)

Table 5-60: 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
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
Small-Scale Digesters							
Dome digester, cooking fuel and light	50 per 1,000 lbs live weight	1.25 per 1,000 lbs live weight	10	CH ₄ : -50%	\$7 energy revenue/savings per head hogs (Vietnam), \$48 energy revenue/savings per head dairy cattle (Tanzania)	Hogs and dairy cattle in selected LPS and management intensities in developing countries	Labor costs, labor share, energy prices
Polyethylene bag digester, cooking fuel and light	20 per 1,000 lbs live weight	0.5 per 1,000 lbs live weight	10	CH ₄ : -50%	\$7 energy revenue/savings per head hogs (Vietnam), \$48 energy revenue/savings per head dairy cattle (Tanzania)	Hogs and dairy cattle in selected LPS and management intensities in developing countries	Labor costs, labor share, energy prices

(continued)

Table 5-60: 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
Centralized Digester							
Centralized digester	163 per head average for hogs across the EU, 1,007 per head average for dairy cattle across the EU	0.07 per head for hogs, 2.06 dairy cattle	20	CH ₄ : -85%	\$8 energy revenue/savings per head for hogs (U.S.) and \$65 energy revenue/savings per head for dairy cattle (U.S.)	Hogs and dairy cattle in selected LPS and management intensities in the EU-27 region	Labor costs, labor share, energy prices

Note: CH₄ reduction efficiencies were assumed to be 85% from baseline for the complete-mix, plug-flow, fixed-film, and large-scale covered lagoon digesters based on the difference between IPCC default emission factors for anaerobic manure management, where CH₄ is released into the atmosphere, and digesters. For the smaller-scale digesters applied in developing countries, the reduction efficiency was assumed to be 50% from baseline, where baseline emissions are much lower because of a different distribution of manure management practices and the likelihood of less efficient CH₄ capture. Because all systems are assumed to capture the same quantity of CH₄ and it was assumed that none of these options affects livestock yields, the benefits per head are constant across system types, providing a given level of CH₄ reduction and energy generation/substitution. Values shown in the table are illustrative based on a single identified country for which the values were estimated but vary widely across countries based on relative labor, energy, and other input costs.

5.3.1.7 References

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5.3.2 Croplands

Land management in croplands influences soil N₂O emissions, CH₄ fluxes, and soil organic carbon stocks (and associated CO₂ fluxes to the atmosphere). Soil N₂O emissions are influenced by human activity, including synthetic nitrogen fertilization practices, application of organic fertilizers such as manure, drainage of organic soils, cultivation of nitrogen-fixing crops, and enhancement of nitrogen mineralization in soils through practices such as cultivation/management of native grasslands and forests (Mosier et al., 1998; Smith et al., 2007).

N₂O is produced naturally in soils through the microbial process of denitrification and nitrification. A number of anthropogenic activities add nitrogen to the soils, thereby increasing the amount of nitrogen available for nitrification and denitrification, and ultimately the amount of N₂O emitted. Anthropogenic activities may add nitrogen to the soils either directly or indirectly.

Direct additions of nitrogen occur from the following activities:

- Various cropping practices, including (1) application of fertilizers; (2) incorporation of crop residues into the soil, including those from nitrogen-fixing crops (e.g., beans, pulses, and alfalfa); and (3) cultivation of high organic content soils (histosols); and
- Livestock waste management, including (1) spreading of livestock wastes on cropland and pasture and (2) direct deposition of wastes by grazing livestock.

Indirect additions occur through volatilization and subsequent atmospheric deposition of ammonia and oxides of nitrogen that originate from (1) the application of fertilizers and livestock wastes onto cropland and pastureland and (2) subsequent surface runoff and leaching of nitrogen from these same sources.

Cultivation of histosols, application of sewage sludge, asymbiotic fixation of soil nitrogen, and mineralization of soil organic matter are additional sources of direct and indirect N₂O emissions on croplands. Emissions from these sources are not calculated or included in these estimates because of a lack of available activity data at the country level. This may result in an underestimate of emissions.

N₂O emissions from agricultural soils calculated herein consist of the following six components:

1. Direct emissions from commercial synthetic fertilizer application (Equation 5.20)
2. Indirect emissions from commercial synthetic fertilizer application (Equation 5.21)
3. Direct emissions from the incorporation of crop residues (Equation 5.22)
4. Indirect emissions from the incorporation of crop residues (Equation 5.23)
5. Direct emissions from manure (pasture, range and paddock and all applied manure) (Equation 5.25)
6. Indirect emissions from manure (Equation 5.26)

5.3.2.1 Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for agricultural soils included nitrogen fertilizer consumption from IFA (2016) or FAO (2016) with growth rates of fertilizer consumption from Tenkerong and Lowenber-DeBoer (2008) and FAO (2012), crop production and area from FAO (2016) with growth rates from IFPRI's IMPACT Model (2017), and animal population data from FAO (2016) with livestock product growth rates from IFPRI (2016).

The Tier 1 basic equations to estimate N₂O emissions from agricultural soils are as follows:

Equation 5.20: Direct N₂O Emissions from Synthetic Fertilizer

$$\text{Direct Emissions from Synthetic Fertilizer (Gg N}_2\text{O)} = F_{SN} * EF_1 * \frac{44}{28} \quad (5.20)$$

where:

- F_{SN} = The annual amount of synthetic fertilizer nitrogen applied to soils (Gg nitrogen)
- EF_1 = Emission factor (equal to 0.01 Gg N₂O-N/Gg nitrogen input)
- $44/28$ = Conversion of N₂O-N to N₂O

Equation 5.21: Indirect N₂O Emissions from Synthetic Fertilizer

$$\begin{aligned} \text{Indirect Emissions from Synthetic Fertilizer (Gg N}_2\text{O)} &= [(F_{SN} * Frac}_{LEACH} * EF_3) + \\ &(F_{SN} * Frac}_{GASF} * EF_4)] * \frac{44}{28} \end{aligned} \quad (5.21)$$

where:

- F_{SN} = Annual amount of synthetic fertilizer nitrogen applied to soils (Gg nitrogen)
- $Frac_{LEACH}$ = Nitrogen lost from leaching and runoff (equal to 0.30 Gg N/Gg N applied in humid countries and equal to 0 in arid countries where leaching and runoff are not likely to occur)
- EF_3 = Emission factor for N₂O emissions from nitrogen leaching and runoff (equal to 0.0075 Gg N₂O-N/Gg N leached or runoff)
- $Frac_{GASF}$ = Fraction of synthetic fertilizer nitrogen that volatilizes as NH₃ and NO_x (equal to 0.10 Gg nitrogen volatilized/Gg nitrogen applied)
- EF_4 = Emission factor for N₂O emissions from nitrogen volatilization (equal to 0.01 Gg N₂O-N/(Gg NH₃-N + NO_x-N volatilized))
- $44/28$ = Conversion of N₂O-N to N₂O

Equation 5.22: Direct N₂O Emissions from Crop Residues

$$\text{Direct Emissions from Crop Residues (Gg N}_2\text{O)} = F_{CR} * EF_1 * \frac{44}{28} * 10^6 \quad (5.22)$$

where:

- F_{CR} = The annual amount of nitrogen in crop residues and forage/pasture renewal (kg nitrogen)
- EF_1 = Emission factor (equal to 0.01 kg N₂O-N/kg nitrogen input)
- $44/28$ = Conversion of N₂O -N to N₂O
- 10^6 = Conversion from kg to Gg

Equation 5.23: Indirect N₂O Emissions from Crop Residues

$$\text{Indirect Emissions from Crop Residues (Gg N}_2\text{O)} = F_{CR} * Frac}_{LEACH} * EF_3 * \frac{44}{28} * 10^6 \quad (5.23)$$

where:

- F_{CR} = The annual amount of nitrogen in crop residues and forage/pasture renewal (kg nitrogen)
- $Frac_{LEACH}$ = Nitrogen lost from leaching and runoff (equal to 0.30 kg N/kg nitrogen applied in humid countries and equal to zero in arid countries where leaching and runoff are not likely to occur)
- EF_3 = Emission factor for N₂O emissions from nitrogen leaching and runoff (equal to 0.0075 kg N₂O-N/kg nitrogen leached or runoff)
- $44/28$ = Conversion of N₂O -N to N₂O

10^6 = Conversion from kg to Gg

Nitrogen additions to soils from crop residues depend on the crop type and yield because different crop types have different nitrogen contents and different amounts of residue typically left in the soil. The equation for F_{CR} is as follows:

Equation 5.24: Annual amount of nitrogen in crop residues and forage/pasture renewal (F_{CR})

$$F_{CR} (Gg N_2O) = \sum_T (Yield Fresh_T * DRY_T * S_T + I_T) * Area_T * (N_{ag(T)} + R_{bg-BIO(T)} * N_{bg(T)}) \quad (5.24)$$

where:

T = Crop or forage type

$Yield Fresh$ = Fresh weight yield of crop (kg fresh weight/ha)

DRY = Dry matter fraction of harvested crop (kg dry matter/kg fresh weight)

S = Slope for above-ground residue dry matter

I = Intercept for above-ground residue dry matter

$Area$ = Total annual area harvested (ha)

N_{ag} = Nitrogen content of above-ground residues (kg N/kg dry matter)

R_{bg-BIO} = Ratio of below-ground residues to above-ground biomass

N_{bg} = Nitrogen content of below-ground residues (kg N/kg dry matter)

Direct N₂O emissions result from livestock manure that is applied to soils through daily spread operations; through application to soils of the residues of already managed manure; or through direct deposition on pasture, range, and paddock by grazing livestock.

Equation 5.25: Direct N₂O Emissions from Manure Applied to Soils

$$\text{Direct Emissions from Manure Applied to Soils (Gg N}_2\text{O)} = [(F_{AM} * EF_1) + (F_{PRP,CPP} * EF_{3PRP,CPP}) + (F_{PRP,SO} * EF_{3PRP,SO})] * \frac{44}{28} \quad (5.25)$$

where:

F_{AM} = Annual amount of manure applied to soils (Gg N / year)

EF_1 = Emission factor (equal to 0.01 Gg N₂O-N/Gg nitrogen input)

F_{PRP} = Annual amount of manure deposited by grazing animals on pasture, range, and paddock (PRP) (Gg N / year)

$EF_{3,PRP}$ = Emission factor for N₂O emissions from manure deposited by grazing animals on PRP (Gg N₂O-N/Gg N)

CPP = Cattle, poultry, and pigs

SO = Sheep and other animals

$44/28$ = Conversion of N₂O-N emissions to N₂O emissions

Equation 5.26: Indirect N₂O Emissions from Manure Applied to Soils

$$\text{Indirect Emissions from Manure Applied to Soils (Gg N}_2\text{O)} = [((F_{AM} + F_{PRP}) * Frac_{LEACH} * EF_3) + ((F_{AM} + F_{PRP}) * Frac_{GASM} * EF_4)] * \frac{44}{28} \quad (5.26)$$

where:

- F_{AM} = Annual amount of manure applied to soils (Gg N/year)
- F_{PRP} = Annual amount of manure deposited by grazing animals on pasture, range, and paddock (PRP) (Gg N/year)
- $Frac_{LEACH}$ = Nitrogen lost from leaching and runoff (equal to 0.30 Gg N/Gg N)
- EF_3 = Emission factor for N₂O emissions from nitrogen leaching and runoff (equal to 0.0075 Gg N₂O-N/Gg N leached or runoff)
- $Frac_{GASM}$ = Fraction of animal manure nitrogen that volatilizes as NH₃ and NO_x (equal to 0.10 Gg nitrogen volatilized/Gg nitrogen applied)
- EF_4 = Emission factor for N₂O emissions from nitrogen volatilization (equal to 0.01 Gg N₂O-N/(Gg NH₃-N + NO_x-N volatilized))
- 44/28 = Conversion of N₂O-N to N₂O

Equation 5.27: Annual amount of managed manure applied to soils (F_{AM})

$$F_{AM} = N_{MMS_Avb} \times [1 - (Frac_{FEED} + Frac_{FUEL} + Frac_{CNST})] \times 10^6 \quad (5.27)$$

where:

- F_{AM} = Annual amount of manure applied to soils (Gg N/year)
- N_{MMS_Avb} = Amount of managed manure nitrogen available for application to managed soils or for feed, fuel, or construction purposes (kg nitrogen yr⁻¹)
- $Frac_{FEED}$ = Fraction of managed manure used for feed (%)
- $Frac_{FUEL}$ = Fraction of managed manure used for fuel (%)
- $Frac_{CNST}$ = Fraction of managed manure used for construction (%)

Using IPCC (2006) Equation 10.34, the EPA estimated managed manure nitrogen available for application to managed soils as follows:

Equation 5.28: Annual amount of managed manure available (N_{MMS_Avb})

$$N_{MMS_Avb} = \sum_S \left\{ \sum_T \left[\left[(N_{(T)} \times Nex_{(T)} \times MS_{(T,S)}) \times \left(1 - \frac{FracLossMS}{100} \right) \right] + (N_{(T)} \times MS_{(T,S)} \times N_{beddingMS}) \right] \right\} \quad (5.28)$$

where:

- N_{MMS_Avb} = Amount of managed manure nitrogen available for application to managed soils or for feed, fuel, or construction purposes (kg nitrogen yr⁻¹)
- $N_{(T)}$ = Number of head of livestock species/category T in the country
- $Nex_{(T)}$ = Annual average nitrogen excretion per animal of species/category T in the country (kg nitrogen animal⁻¹ yr⁻¹)
- $MS_{(T,S)}$ = Fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S in the country (dimensionless)
- $FracLossMS$ = Amount of managed manure nitrogen for livestock category T that is lost in the manure management system S (%)
- $N_{beddingMS}$ = Amount of nitrogen from bedding (to be applied for solid storage and deep bedding manure management system if known organic bedding usage) (kg nitrogen animal⁻¹ yr⁻¹)
- S = Manure management system (MMS)
- T = Species/category of livestock

In all six components of emissions from agricultural soils, activity data (i.e., fertilizer consumption, crop production/area harvested, and livestock populations) were the driving factor for determining emissions.

Activity Data

Direct and Indirect Emissions from Commercial Synthetic Fertilizer Application

Historical

- Commercial synthetic fertilizer consumption data were obtained from the IFA database of fertilizer statistics, known as IFADATA (IFA, 2016), and from the FAO database of agricultural statistics, known as FAOSTAT (FAO, 2016).
- IFA was the preferred source of activity data, and when IFA data were unavailable, FAO data were used. Activity data from at least one of these sources were available for most countries from 1990 through 2014. Specifically, data on the consumption of nitrogenous fertilizer, reported in metric tons of nitrogen⁹⁵ (FAO) or thousand metric tons of nitrogen (IFA), were used.

Projected

- The growth rates of fertilizer consumption from 2015 through 2030 were estimated by using the regional nitrogen fertilizer consumption projections available from Tenkorang and Lowenberg-DeBoer et al. (2008) who provided regional fertilizer use for 2015 and 2030. Countries in a specific region assigned by Tenkorang and Lowenberg-DeBoer et al. (2008) were assigned the same fertilizer consumption growth rates. Fertilizer use for 2020 and 2025 was interpolated. These consumption projections were then used to calculate average annual growth rates for the 5-year increments between 2015 and 2030, which in turn were used to project fertilizer use by country.
- The average annual percentage change in fertilizer use by region for the remainder of the projected time series (i.e., 2030 through 2050) was available from FAO (2012). The average annual regional growth rates for the 5-year increments between 2030 and 2050 were used to project fertilizer use by country. Countries were assigned to regions based on Annex 1 of Tenkorang and Lowenberg-DeBoer (2008) and Appendix 1 of FAO (2012).

Direct and Indirect Emissions from the Incorporation of Crop Residues

Historical

- Historical production and area statistics for the following major crops (residues of which are typically incorporated into soils)—barley, maize, pulses,⁹⁶ rice, sorghum, soybeans, and wheat—were obtained from FAO. Historical production and area data for these crops were available for most countries for 1990 through 2014 (FAO, 2016). For countries for which data were not available, the EPA assumed zero production.

Projected

- The growth rates of crop production and area by crop type for 2015 through 2050 were estimated based on country and regional crop production and area projections developed by IFPRI's IMPACT model (IFPRI, 2017). Projected crop production and area data for all crops through 2050 were obtained from IFPRI by country and subcontinent. When country data were not available, data by subcontinent (e.g., Middle East) were used.
- These production and area projections were used to calculate average annual growth rates for the 5-year increments between 2015 and 2050. For countries for which specific data were unavailable, but the country is known to produce the crop according to FAO (2016), the EPA used the 5-year growth rates for the relevant region and then used the growth rates to project crop production and area by country.

⁹⁵ In the FAO online database, fertilizer data appear to be reported in metric tons, but data are actually reported in metric tons of nitrogen. This was corroborated by paper copies of the FAO statistics.

⁹⁶ Pulses include lentils, dry beans, dry broad beans, dry horse beans, chickpeas, and pulses not elsewhere specified.

*Direct and Indirect Emissions from Manure (Pasture, Range, and Paddock and All Applied Manure)*Historical

- Animal population data for 1990, 1995, 2000, and 2005 through 2014 were obtained from FAO (2016). Populations of nondairy cattle were obtained by subtracting FAO dairy cattle populations from FAO total cattle populations.

Projected

- Emissions from 2015 through 2050 were projected based on livestock product growth rates developed by the IFPRI IMPACT model (IFPRI, 2016). The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, poultry, and milk for the years 2005 through 2050 in 5-year increments. These estimates were used to proxy average annual growth rates for the livestock species, nondairy cattle, swine, sheep, all poultry (including turkeys, ducks, geese, and chickens), and dairy cattle, respectively. For the remaining livestock types, the average population growth rates from 2005 through 2014 in the FAO data were applied.⁹⁷
- Starting with the historical year 2014, FAO animal population statistics, growth rates were applied to calculate projected populations for 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050 for each livestock species.

Emission Factors*Direct and Indirect Emissions from Commercial Synthetic Fertilizer Application*Historical and Projected

- The default Tier 1 emission factors from IPCC (2006) were used to calculate indirect emissions from synthetic fertilizer consumption.
- As recommended in the *2006 IPCC Guidelines* (IPCC, 2006), the EPA assumed that 1% of all nitrogen from fertilizer consumption is directly emitted as N₂O.

*Direct and Indirect Emissions from the Incorporation of Crop Residues*Historical and Projected

- Crop residue factors by crop type as shown in Table 11.2 in the *2006 IPCC Guidelines* (IPCC, 2006) were used; a proxy was used if a default factor was not available for a particular crop.
- N_{bg} for rice and R_{bg-BIO} for sorghum were based on the general “grains” category in the *2006 IPCC Guidelines* (IPCC, 2006).

*Direct and Indirect Emissions from Manure (Pasture, Range, and Paddock and All Applied Manure)*Historical and Projected

- IPCC default nitrogen excretion rates by region and development category were used to estimate nitrogen excretion per head by country for each animal type, based on the country’s region and development category (IPCC, 2006). To use these defaults, we assigned countries to regions (i.e., Africa, Asia, Eastern Europe, Indian Subcontinent, Latin America, Middle East, North America, Oceania, and Western Europe) and development categories (i.e., developed and developing).
- Next, the IPCC guidance methodology on “Coordination with reporting for N₂O emissions from managed soils,” found in Section 10.5.4 of the *2006 IPCC Guidelines* was applied to determine the amount of

⁹⁷ Basing livestock population growth on the 2005 through 2014 historical trend led to unrealistically high growth rates in some countries that have experienced large livestock increases in recent years. In countries where the growth between 2014 and 2050 was greater than 200%, the trend was adjusted to draw on a longer historical period. When possible, the period used was 1990 through 2014; however, in some cases, a shorter period was necessary to keep growth as close as possible to the range considered reasonable (i.e., 200% or less).

nitrogen that remains in manure following management in MMSs. The amount of nitrogen remaining corresponds to the amount available for application to agricultural soils.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

The greatest uncertainties are associated with the completeness of the activity data used to derive the emission estimates. Emissions from fertilizers are only estimated from synthetic fertilizer use. However, organic fertilizers (other than the estimated manure and crop residues) also contribute to N₂O emissions from soils, but this activity is not captured in these estimates. Crop residues from crops other than those covered (including from nitrogen-fixing crops other than soybeans and pulses) may be left on the field, thus resulting in N₂O emissions. The identity and quantity of these crops vary among the different countries.

The livestock nitrogen excretion values, while based on detailed population statistics and regional nitrogen excretion factors, do not accurately reflect country-to-country variations in animal weight or feeding regimes. Any contribution of animal bedding materials to manure nitrogen was not considered. The “other” category for manure management is a large unknown—the EPA assumed no emissions from this category, except for from poultry, where the “other” category was assumed to represent an average of the “poultry with litter” and “poultry without litter” management systems. Finally, emissions from histosols, sewage sludge, symbiotic fixation of soil nitrogen, and mineralization of soil organic matter are not calculated or included in these estimates because of a lack of available activity data at the country level. The last two sources, in particular, can be a significant component of agricultural soil emissions.

Uncertainty also exists in the projected emissions. For some subcategories, projections are not available to 2050, so projections from earlier periods were used. Additionally, in some cases projections are on a regional level, not a country-specific level, and using regional projections increases uncertainty. Economic and environmental agricultural policies and improved farming practices are also factors that affect emissions from agricultural soil management. Because of the complexities of agricultural product markets and the influences of disruptions in the industry (such as food safety issues), many of these factors are hard to predict, thereby contributing to the uncertainty of emission projections for this source.

Historical Data Assumptions

The EPA used the following assumptions for countries with incomplete data.

Direct and Indirect Emissions from Commercial Synthetic Fertilizer Application

Eritrea before 1993. In 1993, the former People’s Democratic Republic of Ethiopia (Ethiopia PDR) divided into Ethiopia and Eritrea. Data for Ethiopia for 1990 through 2014 were available from IFA, but data for Eritrea were not. To estimate the fertilizer consumption of Eritrea in 1990, the EPA determined the relative ratio of the fertilizer consumption of the current Eritrea and Ethiopia in 1993. This ratio (2% for fertilizer consumption) was then applied to the fertilizer consumption of Ethiopia PDR to estimate the fertilizer consumption of Eritrea for 1990. This method assumed that the IFA data for Ethiopia in 1990 included only the portion of Ethiopia PDR that would become Ethiopia and not the portion that would become Eritrea.

Belgium-Luxembourg before 2000. In 2000, Belgium and Luxembourg began reporting separately to FAO, rather than together, as had been the case previously. The distribution of fertilizer consumption between these two countries in 2000 was assumed to be the same for 1990 and 1995. Consequently, Belgium-Luxembourg consumption in 1990 and 1995 was allocated between Belgium and Luxembourg by their relative percentages in 2000.

The former Yugoslavia before 1995. In 1995, Yugoslavia divided into separate countries. The distribution of fertilizer consumption among the former Yugoslav countries in 1995 was assumed to be the same for 1990. Consequently, Yugoslavia consumption in 1990 was allocated among the former Yugoslav countries according to their relative percentages in 1995. Montenegro was not reported separately from Serbia at any point, and it was assumed that this country had zero synthetic fertilizer consumption (i.e., all consumption was allocated to Serbia).

The former Czechoslovakia before 1993. In 1993, Czechoslovakia divided into the Czech and Slovak Republics. The distribution of fertilizer consumption between these two countries in 1993 was assumed to be the same for 1990. Consequently, Czechoslovakia consumption in 1990 was allocated between the Czech and Slovak Republics by their relative percentages in 1993.

IFA reports data for FSU states dating back to 1990 (before the breakup of the Soviet Union), so there was no need to separate out Soviet Union data for 1990, as would have to be done with FAO data, which were not reported separately in 1990.

Portions of the FAO time series for particular countries were determined to be outliers because they differed significantly from other parts of the time series and did not line up with trends in other parts of the time series. In such cases, the rest of the time series was extrapolated to replace the outlier data point. This was the case for Algeria, Benin, Nepal, and United Arab Emirates for 2005. In addition, the entire FAO time series for Bahrain was not used because of significant and extreme variations in reported fertilizer use. In these two cases, no other data were available, and fertilizer use was assumed to be zero.

Direct and Indirect Emissions from the Incorporation of Crop Residues

The FSU before 1993. In 1993, the Soviet Union divided into separate countries (in the context of FAO reporting—the political dissolution occurred in 1991). The distribution of crop production and area among the FSU countries in 1993 was assumed to be the same for 1990. Consequently, Soviet crop production and area in 1990 were allocated among the FSU countries by their relative percentages in 1993.

The former Yugoslavia before 1995. In 1995, Yugoslavia divided into separate countries. The distribution of crop production and area among the former Yugoslav countries in 1995 was assumed to be the same for 1990. Consequently, Yugoslavia crop production and area in 1990 were allocated among the former Yugoslav countries according to their relative percentages in 1995. Montenegro was not reported separately from Serbia at any point, and it was assumed that this country had zero crop production and area (i.e., all production and harvested area were allocated to Serbia).

The former Czechoslovakia before 1993. As noted above, in 1993, Czechoslovakia divided into the Czech and Slovak Republics. The distribution of crop production and area between these two countries in 1993 was assumed to be the same for 1990. Consequently, Czechoslovakia crop production and area in 1990 were allocated between the Czech and Slovak Republics by their relative percentages in 1993.

Ethiopia and Eritrea before 1993. As noted above, in 1993, Ethiopia PDR divided into Ethiopia and Eritrea. The distribution of crop production and area between these two countries in 1993 was assumed to be the same for 1990. Consequently, Ethiopia PDR crop production and area in 1990 were allocated between Ethiopia and Eritrea by their relative percentages in 1993.

Belgium-Luxembourg before 2000. As noted above, in 2000, Belgium and Luxembourg began reporting separately to FAO, rather than together, as had previously been the case. The distribution of crop production and area between these two countries in 2000 was assumed to be the same for 1990 and 1995. Consequently, Belgium-Luxembourg crop production and area in 1990 and 1995 were allocated between Belgium and Luxembourg by their relative percentages in 2000.

Direct and Indirect Emissions from Manure (Pasture, Range, and Paddock and All Applied Manure)

In 1990, animal population data were not available for certain countries that were formed after the breakup of the FSU (Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan), Yugoslavia (Bosnia, Croatia, Macedonia, Slovenia, and Serbia and Montenegro), Czechoslovakia (Czech Republic and Slovakia), and Ethiopia (Ethiopia and Eritrea).

In addition, Belgium and Luxembourg were reported jointly until 2000. Therefore, for each region, the EPA determined the percentage contribution of each country to its regional total using 1995 (1993 for Czechoslovakia) or 2000 animal population data. The EPA then applied these percentages to estimate 1990 and/or 1995 animal population for these countries. The animal types included were dairy cows, other cattle, buffalo, sheep, goats, pigs, chickens, turkeys, ducks, geese, horses, mules, asses, camels, and other camelids (assumed to be llamas and alpacas).

5.3.2.2 Mitigation Options Considered for Croplands

This section estimates global non-CO₂ mitigation potential from croplands using DAYCENT, a gridded global biophysical model. Given that a key goal of this study is to generate global mitigation estimates for all regions of the globe, we focused on applying models capable of characterizing emissions and yields across the globe under alternative scenarios rather than limiting the study to crop/region combinations where long-term empirical data are available for case studies. Using a spatially differentiated biophysical model improves the analysis by incorporating differences in soil characteristics and dynamic soil processes, climate, and management practices, as well as crop-specific nutrient uptake and plant physiology. It allows us to model mitigation consistently across the entire world, capturing differentiation in underlying characteristics that affect simulation results for both baseline and mitigation practices between countries. All gridded mitigation estimates are defined relative to the baseline conditions for that point. This enables us to capture differences in yield response to altering nutrient management practices, for instance, based on the initial level of nutrient availability.

The mitigation options considered in this study include:⁹⁸

- **No Till:** All cultivation and field preparation events were removed except for seeding, which occurred directly into the residue.
- **Reduced Fertilization:** Baseline fertilizer application levels were reduced by 20%.
- **Increased Fertilization:** Baseline fertilizer application levels were increased by 20%.
- **Split Nitrogen Fertilization:** Under this option, the baseline nitrogen 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 (following Del Grosso et al. [2009]).
- **Nitrification Inhibitors:** The baseline nitrogen application amount was applied once annually on the date of planting. Nitrification inhibitors were applied at the time of fertilization and reduced nitrification by 50% for 8 weeks (following Del Grosso et al. [2009] and Branson et al. [1992]).
- **100% Residue Incorporation:** In this option, all crop residue was assumed to remain after harvest. This option serves to evaluate how reducing removals would affect soil organic carbon stocks.

While using a biophysical model is important for globally consistent spatially differentiated estimation of mitigation potential and cost, it comes with a number of restrictions. First, to assess cropland mitigation potential and costs, DAYCENT-simulated yields and emissions under each mitigation option are compared to DAYCENT-

⁹⁸ Additional mitigation options (e.g., reduced tillage, other N process inhibitors, slow release fertilizers) may be considered in future studies, depending on the level of potential mitigation and data availability for inclusion within DAYCENT.

simulated baseline conditions⁹⁹ to calculate proportionate changes in a consistent manner. However, baseline emissions simulated by DAYCENT differ from the baseline estimates of emissions as calculated above.¹⁰⁰ Because dynamic soil processes are represented, treatments were held constant over time to focus on the dynamics of changes in yields and emissions relative to baseline conditions. Specifically, fertilizer applications are held constant in the DAYCENT baseline. Instead, alternative fertilizer rates appear in the GHG mitigation strategies evaluated below.

Second, it is important to note that this analysis currently models the effects of applying mitigation strategies to only a fraction of the total emissions from agriculture, focusing on emissions from major crops (with mitigation scenario estimates applied to similar minor crops in some cases) where there are sufficient data available for model calibration. Crops accounting for about two-thirds of global cropland are simulated within DAYCENT.¹⁰¹ See Table 5-61 for a description of the input data used in the DAYCENT simulations. Specifically, the following types of emissions and crops 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)

⁹⁹ Baseline conditions for each modeled crop in each region were simulated using DAYCENT based on data characterizing climate, soils, and management practices.

¹⁰⁰ There are substantial differences in the baseline emissions from agricultural soils presented in the GER analyses and those utilized in calculating mitigation potential. The GER emissions are based on country-reported values or Tier 1 calculations, whereas DAYCENT calculates emissions using global gridded data and crop-specific nonlinear functions. The DAYCENT simulations are expected to provide estimates of mitigation potential that better reflect differences across crops as well as spatial differences in soil, climate, cultivar, management, and other key factors, but they are only available for the subset of crops for which sufficient data were available to adequately calibrate the model. In addition, the DAYCENT simulations held fertilizer use constant during the simulation period to focus on the dynamic response of emissions to changes in management. However, fertilizer use is projected to rise substantially over time in the GER, leading to increasing divergence in the baseline emission estimates over time for the subset of crops that are consistent between the two baselines. Given differences in mitigation options between cropland and grassland as well as the nonlinear relationships between soil, climate, and management and the resulting yields and GHG emissions, there is no readily available method for applying the available estimates of the effects of cropland mitigation options from DAYCENT to additional crops or to grasslands. Thus, the baseline used for comparison to the mitigation scenarios reflects only a subset of total emissions from agricultural soils. Similarly, the GHG emissions potential reported reflect only a subset of the total potential reductions available from agricultural soils. Expanding the scope of GHG emissions from agricultural soils for which mitigation potential and costs have been estimated is an important area of future research.

¹⁰¹ Thus, mitigation potential presented here is an underestimate of mitigation that could be achieved if these mitigation options were applied to nonmodeled crops. There is additional mitigation potential associated with managed grasslands that is not captured here but is an important topic for future research.

Table 5-61: Description of the Input Data Used in DAYCENT Simulations

Data Type	Description	Source
Daily weather	Daily weather for 1901–2010 at 0.5° resolution in latitude by longitude. This includes daily minimum temperature, daily maximum temperature, and daily precipitation.	The original data source was the MsTMIP project's 6-hour CRU + NCEP combined data. This was aggregated to daily, and all nonland cells were removed. http://nacp.ornl.gov/MsTMIP.shtml
Soils	These data are the same as data used for the previous DAYCENT global simulations. The data are at 0.5° resolution in latitude by longitude and include sand, silt, clay, bulk density, pH, and number of soil layers.	Food and Agriculture Organization. 1996. The Digitized Soil Map of the World Including Derived Soil Properties. CDROM. Rome: FAO.
Agricultural cells to simulate	This mask was computed from the fraction of agricultural area. The fraction of agricultural area is provided at a 5-minute resolution in latitude by longitude. These data were aggregated to 0.5° resolution by latitude and longitude then we selected cells where fraction of cropland area \geq 5% of the grid cell area.	Agricultural Lands in the Year 2000. Described in the publication, Ramankutty et al. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. <i>Global Biogeochemical Cycles</i> 22, GB1003. doi:10.1029/2007GB002952.
Crop masks for maize, winter wheat, spring wheat, winter barley, spring barley, sorghum, and soybean	Crop-specific masks indicating where to simulate each crop. Each crop mask is a subset of the agricultural cells to simulate, described above. This data was provided at 0.5° resolution in latitude by longitude. Note: Although separate crop masks were provided for winter and spring wheat, there was almost no difference between these masks. Likewise for winter and spring barley. The main difference between winter and spring varieties was the planting and harvest dates (see below).	These files were produced by Mirella Salvatore at the FAO and Aaron Berdanier. Personal communication.
Irrigated areas by crop type	Crop-specific data with the fraction of cropland area that is irrigated. These data were provided at 0.5° resolution in latitude by longitude for all years between 1985 and 2008. Irrigation was simulated for modern agriculture (year 1951 or later) for cells where the irrigated fraction > 0.0 for any year between 1985 and 2008. The fraction of cropland irrigated in 2008 was used in the post-processing step to aggregate model results.	These files were produced by Mirella Salvatore at the FAO and Aaron Berdanier. Personal communication.

(continued)

Table 5-61: Description of the Input Data Used in DAYCENT Simulations (continued)

Data Type	Description	Source
Initial year of cultivation	Fraction of area in agriculture for years 1700–2007 at 0.5° resolution in latitude by longitude. We computed the first year when the fraction of agricultural area was 50% of the fraction of cropland area in 2000; this determined the year of plow-out for the cell.	Global Cropland and Pasture Data from 1700–2007. This is a beta release of an updated version of the DAYCENT original historical cropland dataset that spanned the 1700–1992 period. The original dataset was described in the publication by Ramankutty and Foley (1999) in Global Biogeochemical Cycles. This release updates the data to the 1700–2007 time period.
Crop-specific planting and harvest dates	Planting date (<u>day of year</u>) and harvest date (<u>day of year</u>) for each crop at 0.5° resolution in latitude by longitude: barley (winter), barley (spring), maize (main season), maize(second season), sorghum (main season), sorghum second season), soybeans, wheat (winter), wheat (spring)	Sacks, W.J., D. Deryng, J.A. Foley, and N. Ramankutty. 2010. Crop planting dates: An analysis of global patterns. <i>Global Ecology and Biogeography</i> 19, 607–620. doi:10.1111/j.1466-8238.2010.00551.x.
Harvest type and residue removal rate by crop.	Harvest type and residue removal rate by crop at 0.5° resolution in latitude by longitude by crop. The harvest type designates a grain or nongrain harvest (for this exercise, all crops had grain harvests). The residue removal rate determines the percentage of residue removed from the field at time of harvest. Residue includes all above-ground plant material after grain is removed.	These files were produced by Mirella Salvatore at the FAO and Aaron Berdanier. Personal communication.
Tillage, planting, and weeding practices by country and by crop	Tillage, planting, and weeding practices by crop for developed countries (conventional), developing countries (conservation), and less developed countries. Crops are categorized as small grain (barley, wheat) or large grain (maize, sorghum, soybean). These practices determine the intensity of soil disturbance simulated for each event.	These files were produced by Mirella Salvatore at the FAO and Aaron Berdanier. Personal communication.
N application rates include fertilizer nitrogen and manure nitrogen	Annual nitrogen application rates including nitrogen fertilizer plus manure nitrogen ($\text{gN m}^{-2} \text{ yr}^{-1}$) at 0.5° resolution in latitude by longitude by crop for years 1985–2008. Nitrogen application rates from 1950–1984 were linearly interpolated between 0.0 in 1950 and the 1985 rate. Nitrogen application rates for 2009–2035 were set to the 2008 rate. Note: There were no data about the relative amount of fertilizer nitrogen and manure nitrogen.	These files were produced by Mirella Salvatore at the FAO and Aaron Berdanier, Personal communication.

(continued)

Table 5-61: Description of the Input Data Used in DAYCENT Simulations (continued)

Data Type	Description	Source
Harvested areas and yields by crop type in year 2000.	Harvested area (proportion of grid cell area) and yield (tons/ha). The data are provided at 5-minute resolution in latitude by longitude. We aggregated the data to a 0.5° resolution. The measured yields were compared with simulated yields from the baseline simulation. The harvested area fraction was used in the post-processing step for aggregating model results.	Harvested area and yields of 175 crops (M3-Crops Data). Monfreda et al. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. <i>Global Biogeochemical Cycles</i> 22, GB1022. doi:10.1029/2007GB002947.

Compared with the projections reported above, this discussion excludes rice (soils and cultivation) which treated separately below. Furthermore, compared to the estimates typically developed for GHG inventories, the emissions presented in this section are lower because the following types of emissions were excluded because of data limitations and a lack of mitigation options:

- Drainage of organic soils.
- Grassland soils, including pasture
- 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 options that can be applied to mitigate emissions from these major crops in this section.

The mitigation options evaluated in this analysis were based on a review of the literature to identify the most promising options, while also considering data availability and the potential for modeling within DAYCENT. The mitigation options represent alternative management practices that would alter crop yields and the associated GHG emissions, including adoption of no-till management, split nitrogen fertilization applications, application of nitrification inhibitors, increased nitrogen fertilization (20% increase over BAU),¹⁰² decreased nitrogen fertilization (20% reduction from BAU), and 100% crop residue incorporation.

The nitrogen management practices (split nitrogen fertilization, nitrification inhibitors, increased and decreased nitrogen fertilization) influence N₂O emissions in addition to soil organic carbon stocks due to reduced or enhanced carbon inputs associated with the level of crop production. Smith et al. (2007) estimated that 89% of the overall technical potential for mitigation of agricultural GHG emissions is associated with carbon sequestration in soils. Although soil organic carbon 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 C both influence and are influenced

¹⁰² Baseline fertilizer levels vary across grid cells. As noted in Table 6-61, global gridded fertilizer rates were provided by Mirella Salvatore at the FAO and Aaron Berdanier, personal communication. For the purposes of this analysis, we explored the potential effects of increasing and decreasing N fertilizer application rates by 20%. Those values were selected to represent a reasonable range of changes in fertilizer application. Depending on baseline fertilizer rates, some regions see relatively little reduction in yields from a 20% reduction, while others see a much more substantial yield decrease. Increasing fertilizer levels generally increases N₂O emissions (though also tends to increase soil carbon), but there are some countries, particularly in Sub-Saharan Africa, where increasing fertilizer rates results in a reduction in GHG intensity (i.e., reduction in emissions per unit of output). The primary rationale for including an increase in fertilizer rate was to reflect the potential for reduced emission intensity and lower emissions in a constant crop production scenario.

by cropland productivity. Other things being equal, higher crop yields may increase soil carbon wherever more crop residue can be incorporated into the soil. Similarly, reducing crop residue removal would affect soil organic carbon stocks by changing the amount of carbon 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 C by enhancing carbon inputs to soils from greater crop production or decrease the losses of carbon from soils with lower decomposition rates (Paustian et al., 1997; Six et al., 2000).

5.3.2.3 Technical Characteristics of Options

For the purposes of this analysis of the technical mitigation potential from croplands soils, all options are available in all regions and all time periods, though only options that result in emission reductions for a given crop/region combination are retained in the MAC curves. Options related to fertilization are applicable where baseline fertilizer application levels are nonzero. The changes in emissions and yield for each crop/region/year combination modeled were simulated in the DAYCENT model. Table 5-62 presents the base yields for each modeled crop type and the difference from base yield impacts associated with the mitigation option over time.

Table 5-62: DAYCENT Base Mean Yields and Differences from Mean Yield for Mitigation Strategies, by Year (Metric Tons of Grain per Hectare)

Mitigation Strategy	2015	2020	2025	2030
Maize				
Base yield ^a	3.64	3.64	3.59	3.60
No till	-0.25	-0.17	-0.12	-0.07
Optimal nitrogen fertilization ^b	2.9	3.05	3.1	3.08
Split nitrogen fertilization	0.16	0.17	0.19	0.18
100% residue incorporation	0.23	0.24	0.24	0.24
Nitrification inhibitors	-0.01	-0.01	-0.01	-0.01
Reduced fertilization	-0.36	-0.39	-0.4	-0.4
Increased fertilization	0.28	0.29	0.31	0.31
Sorghum				
Base yield ^a	2.34	2.35	2.33	2.32
No till	-0.18	-0.13	-0.1	-0.06
Optimal nitrogen fertilization ^b	3.07	3.27	3.19	3.25
Split nitrogen fertilization	0.14	0.14	0.13	0.14
100% residue incorporation	0.15	0.17	0.16	0.17
Nitrification inhibitors	-0.02	-0.03	-0.02	-0.02
Reduced fertilization	-0.22	-0.25	-0.26	-0.27
Increased fertilization	0.19	0.22	0.22	0.23

(continued)

Table 5-62: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric Tons of Grain per Hectare) (continued)

Mitigation Strategy	2015	2020	2025	2030
Winter Wheat				
Base yield ^a	2.92	2.89	2.8	2.87
No-till	-0.13	-0.11	-0.07	-0.05
Optimal nitrogen fertilization ^b	1.55	1.82	1.87	1.78
Split nitrogen fertilization	0.09	0.1	0.11	0.11
100% residue incorporation	0.11	0.12	0.13	0.12
Nitrification inhibitors	0.03	0.04	0.04	0.05
Reduced fertilization	-0.22	-0.26	-0.25	-0.27
Increased fertilization	0.19	0.2	0.2	0.21
Spring Wheat				
Base yield ^a	2.94	2.92	2.85	2.83
No till	-0.16	-0.13	-0.1	-0.08
Optimal nitrogen fertilization ^b	1.49	1.46	1.4	1.36
Split nitrogen fertilization	0.07	0.08	0.08	0.08
100% residue incorporation	0.11	0.11	0.11	0.11
Nitrification inhibitors	0.02	0.03	0.03	0.03
Reduced fertilization	-0.2	-0.22	-0.21	-0.21
Increased fertilization	0.14	0.15	0.14	0.14
Winter Barley				
Base yield ^a	3.59	3.58	3.5	3.57
No till	-0.2	-0.21	-0.15	-0.1
Optimal nitrogen fertilization ^b	2.64	3.11	3.07	3
Split nitrogen fertilization	0.04	0.06	0.06	0.05
100% residue incorporation	0.37	0.39	0.39	0.39
Nitrification inhibitors	0.01	0.03	0.03	0.03
Reduced fertilization	-0.34	-0.39	-0.41	-0.43
Increased fertilization	0.31	0.35	0.36	0.38
Spring Barley				
Base yield ^a	2.83	2.79	2.77	2.77
No till	-0.29	-0.24	-0.2	-0.17
Optimal nitrogen fertilization ^b	1.8	1.8	1.67	1.63
Split nitrogen fertilization	0.08	0.09	0.09	0.08
100% residue incorporation	0.21	0.22	0.21	0.21
Nitrification inhibitors	0.01	0.02	0.02	0.02
Reduced fertilization	-0.28	-0.31	-0.31	-0.32
Increased fertilization	0.24	0.26	0.25	0.25

(continued)

Table 5-62: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric Tons of Grain per Hectare) (continued)

Mitigation Strategy	2015	2020	2025	2030
Soybeans				
Base yield ^a	2.95	2.94	2.92	2.92
No till	-0.02	-0.02	-0.01	-0.01
Optimal nitrogen fertilization ^b	0.06	0.07	0.07	0.07
Split nitrogen fertilization	0	0	0	0
100% residue incorporation	0.02	0.02	0.02	0.02
Nitrification inhibitors	0	0.01	0.01	0.01
Reduced fertilization	-0.01	-0.01	-0.01	-0.01
Increased fertilization	0.01	0.01	0.01	0.01

^a Base yield values represent production with no mitigation options, subsequent rows under each commodity presents relative change from base yield values. ^b Optimal nitrogen fertilization simulates providing sufficient N to meet crop needs in each daily timestep of the DAYCENT model. This option was excluded from the main MAC analysis; values are presented for information only.

5.3.2.4 Economic Characteristics of Options

In cases where yields decrease as a result of the mitigation option, we valued the reduction in production at the market price and included no tax or other benefits. Details of the costs associated with each mitigation option are listed below.

- **No Till:** Reductions in labor costs are associated with the reduction in field preparation that are based on data from USDA's Agricultural Resource Management Survey 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 fewer passes over the field are needed, which leads to reduced equipment depreciation. Thus, no incremental capital costs were assumed for no-till adoption.
- **Reduced Fertilization:** This option reduces operation costs by the value of the fertilizer withheld, which varies across crop/region/year combinations based on baseline fertilizer application rates and prices. We assumed that other costs of fertilizer application are unchanged.
- **Increased Fertilization:** This option increases operation costs by the value of the additional fertilizer used, which varies across crop/region/year combinations based on baseline fertilizer application rates and prices. We assumed that other costs of fertilizer application are unchanged.
- **Split Nitrogen Fertilization:** 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.
- **Nitrification Inhibitors:** 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. We assumed that this option does not affect any other costs of fertilizer application.
- **100% Residue Incorporation:** No cost is associated with this option.

Description of the DAYCENT Model

This analysis used the DAYCENT ecosystem model to estimate crop yields, N₂O and CH₄ emissions, and soil carbon stocks. DAYCENT is a process-based model (Parton et al., 1998; Del Grosso et al., 2001) that simulates biogeochemical carbon and nitrogen 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 uses the soil carbon modeling framework developed in the Century model (Parton et al., 1987, 1988, 1994; Metherell et al., 1993), with refinement to simulate carbon dynamics at a daily time-step. Key processes simulated by DAYCENT include crop production, organic matter formation and decomposition, and 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 the EPA to develop the soil carbon and soil estimates for the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2013) submitted to the UNFCCC.

DAYCENT simulated crop yields, direct N₂O and CH₄ emissions, and soil organic carbon stock changes at a 0.5°grid resolution. Indirect N₂O emissions were estimated base on simulated amounts of nitrate leaching, nitrogen runoff in overland water flow, and NO_x emissions from a site according to the DAYCENT model combined with the IPCC default factors for indirect N₂O emissions (De Klein et al., 2006). To represent the longer term effect of cultivation on soil C, simulations started in 1700 after a simulation of 3,000 years of native vegetation, which is a similar procedure to the methods applied in the U.S. Greenhouse Gas Inventory for agricultural soil carbon and N₂O (EPA, 2013). 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. 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.

We established projected baseline emissions and crop production for both irrigated and rainfed production systems using simulated yields and GHG emission rates from the DAYCENT model and adjusting with projected growth rates of these production systems from IFPRI's 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 the IMPACT model reflect socioeconomic drivers such as population growth and technological changes to meet global food demand (Nelson et al., 2010).

The croplands analysis, through its use of a dynamic biophysical crop model, captures the effect of fertilizer applications on plant growth and, hence, on CO₂ sequestration and soil carbon storage. These effects, where applicable, are important. However, soil carbon levels tend to stabilize in a period of a decade or so, so the resulting abatement potential in later years is reduced.

Several limitations are worth noting in the croplands analysis. Coverage was limited to major crops, and pasture was excluded. As a result, the mitigation potential, compared with the sector baseline as a whole, is limited.

5.3.2.5 References

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5.3.3 Rice Cultivation

Rice cultivation consists of CH₄ emissions from rice production. The anaerobic decomposition of organic matter in flooded rice fields produces CH₄. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and flood water, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, CH₄ is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. Several factors influence the amount of CH₄ produced, including water management practices and the quantity of organic material available to decompose.

N₂O emissions from rice cultivation associated with fertilizer, crop residues, and other N additions to soils are captured in Section 5.3.3.1, Projections Methodology. This section evaluates CH₄ emissions from rice cultivation as described above. Conversely, the mitigation analysis in Section 5.3.3.2, Mitigation Options Considered for Rice Cultivation, presents both N₂O and CH₄ mitigation from rice cultivation together.

5.3.3.1 Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for rice cultivation included rice area harvested from FAO (2016), type of water management regime and rice-growing season length from GRiSP (2013), and growth rate of rice area harvested from IFPRI's IMPACT model (2017).

The Tier 1 basic equation to estimate CH₄ is as follows:

$$CH_4 \text{ Emissions from Rice Cultivation (Gg CH}_4) = \sum_{i,j,k} (EF_{i,j,k} * t_{i,j,k} * A_{i,j,k} * 10^{-6}) \quad (5.29)$$

where:

- $EF_{i,j,k}$ = A daily emission factor for i, j , and k conditions (kg CH₄ ha⁻¹ day⁻¹)
- $t_{i,j,k}$ = Cultivation period of rice for i, j , and k conditions (days)
- $A_{i,j,k}$ = Annual harvested area of rice for i, j , and k conditions (ha yr⁻¹)
- i, j , and k = Represent different ecosystems, water regimes, type and amount of organic amendments, and other conditions under which CH₄ emissions from rice may vary

Rice emissions vary according to the conditions under which rice is grown. Using the approach outlined above, the harvested area can be subdivided by different growing conditions (e.g., water management regime) and multiplied by an emission factor appropriate to the conditions. The sum of these individual products represents the total national estimate.

In practice, it is difficult to obtain specific emission factors for each commonly occurring set of rice production conditions in a country, so the *2006 IPCC Guidelines* instruct countries to first obtain a baseline emission factor, the seasonally integrated emission factor for continuously flooded fields without organic amendments (EF_c). Different scaling factors were then applied to this seasonally integrated emission factor to obtain an adjusted seasonally integrated emission factor for the harvested area as follows:

$$EF_i = EF_c * SF_w * SF_o * SF_s \quad (5.30)$$

where:

- EF_i = Adjusted seasonally integrated emission factor for a particular harvested area
- EF_c = Seasonally integrated emission factor for continuously flooded fields without organic amendments
- SF_w = Scaling factor to account for the differences in ecosystem and water management regime
- SF_o = Scaling factors for organic amendments (should vary for both type and amount of amendment applied)
- SF_s = Scaling factor for soil type, if available.

For emissions from rice cultivation, activity data (i.e., rice area harvested), water management regime, and the length of the rice-growing season were the driving factors for determining emissions.

Activity Data

Historical

- Area harvested for rice cultivation from 1990 through 2014 was obtained from FAO's FAOSTAT Statistical Database (FAO, 2016). If the harvested area was not available from FAO statistics, it was assumed that the country did not grow rice.
- Information on the type of water management regime (irrigated, rainfed lowland, upland, or deepwater) was obtained from the Global Rice Science Partnership (GRiSP) *Rice Almanac*, 4th edition (GRiSP, 2013). If a country's water management regime was not available in the *Rice Almanac*, the EPA used the regime data from the IRRI World Rice Statistics, which is consistent with previous updates to this report (IRRI, 2009).
- Information on the length of the rice-growing season in each country was also obtained from the *Rice Almanac* (GRiSP, 2013). If a country's rice-growing season lengths were not available in the *Rice Almanac*, the EPA used the rice-growing season length from the IRRI World Rice Statistics, which is consistent with previous updates to this report (IRRI, 2009).

Projected

- A 5-year growth rate of rice area harvested data was estimated for 2015 through 2050 by using the country rice area harvested projections developed by IFPRI's IMPACT model (IFPRI, 2017).¹⁰³
- For countries where projected area data were not available, regional (i.e., Africa, Americas, Asia, Europe, or Oceania) area 5-year growth rates from the same IFPRI IMPACT model (IFPRI, 2017) were used.
- A 1-year area growth rate based on IFPRI data was applied to historical 2014 emissions to develop 2015 projections. Five-year area growth rates were then applied to the 2015 emissions attributed to rice cultivation to develop projections at 5-year intervals through 2050.

Emission Factors

Historical and Projected

- Country-applicable daily emission factors were developed for each of the five main water management types: continuously flooded, irrigated, rainfed lowland, upland, or deepwater.
- The starting point (baseline) emission factor (1.3 kg CH₄/ha-day) obtained from the 2006 *IPCC Guidelines* (IPCC, 2006) assumes fields with no flooding for less than 180 days prior to rice cultivation and continuously flooded fields during rice cultivation without organic amendments. Scaling factors from the 2006 *IPCC Guidelines* (IPCC, 2006) were then applied to adjust the starting-point emission factor for each of the other water regimes based on the factors for the pre-cultivation and cultivation periods. A scaling factor of 1.22 was used for the pre-cultivation period for all water regimes except upland cultivation. The

¹⁰³ The IFPRI IMPACT model incorporates supply and demand parameters to determine the estimated growth rates. These parameters include the feed mix applied according to relative price movements, international trade, national income, population, and urban growth rates, as well as anticipated changes in these rates over time.

scaling factors 0.78, 0.28, 0.31, and 0 were used for the rice cultivation period for irrigated, regular rainfed (lowland), deepwater, and upland, respectively.

- The combination of all the above adjustment factors provided the adjusted country-specific emission factors used in the emission equation above.
- A weighted average of the water-regime-based emission factors for each country was calculated based on the percentage of each regime in that country. This weighting gives the combined final daily emission factor for each country.

Season Lengths

Country-applicable season lengths were based on the *Rice Almanac* (GRiSP, 2013). Season lengths were given as month ranges for planting and harvest (e.g., planting: February through March, harvest: mid-June through mid-July). To estimate the number of days corresponding to the given range, the EPA made the following assumptions:

- A single month given (e.g., March, rather than a range, March–April) was assumed to refer to the 15th of that month; “mid” refers to the 15th of the month; “early” refers to the 1st of the month; and “late” refers to the last day of the month.
- A range of months was assumed to refer to the 1st or 15th day of the month, falling in the approximate middle of the range, as applicable. For example, April–May would return May 1st; April–June would return May 15th; late November–January would return Jan 1st.
- For countries with more than one season per year (i.e., “main,” “second”), season lengths were added. For countries with early and late seasons, the longer of the two seasons was used. For countries where GRiSP identified different rice-growing regions, the regional season lengths were averaged.

Area harvested data for 1990, 1995, 2000, 2005, 2010, and 2014 were multiplied by the combined final daily emission factor and by the season length.

Emission Reductions in Baseline Scenario

The methodology used for this source category does not explicitly model any emission reductions; however, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainties

Significant uncertainties exist in the CH₄ emission estimates from rice cultivation. The greatest uncertainties are associated with the use of default emission factors. The IPCC emission factors are not country specific and are adjusted for some parameters (e.g., water management) but not adjusted for other parameters (e.g., rationing). Water regime information was not available for several other countries, and using the default emission factor for these countries may lead to an overestimate of emissions. In addition, country-specific information is not readily available on the amount of flooding and aeration in irrigated areas, so assumptions had to be developed based on country conditions.

If a country-specific emission factor was not available and a country was used as a proxy for season length, the same country proxy was used. Otherwise the baseline emission factor (1.3) was used. The following country proxies were applied:

- Madagascar’s emission factor was applied to Comoros.
- Malaysia’s emission factor was applied to Brunei Darussalam.

Because of limited information, all irrigated land was assumed to be continuously flooded with no aeration. This assumption is conservative and could lead to overestimates in emissions.

Also, no scaling adjustment was made to account for organic amendments, because of a lack of data on the use of such amendments. This may result in an underestimate of emissions.

The rice season length is also an area of uncertainty, because many assumptions were made to turn a rough estimate of month ranges into a specific number of days. In addition, a number of countries' rice season lengths were proxied because of a lack of data, and these proxies for season length might not be accurate. For some countries where FAO indicated that rice is grown, no season length data were available, and for some countries the available data were problematic (e.g., planting dates overlapped with harvest dates). In both of these cases, countries in the same region deemed to have similar climates or rice-growing schemes were used as proxies.

5.3.3.2 *Mitigation Options Considered for Rice Cultivation*

This section presents the methodology for estimating mitigation from the rice sector. Both N₂O and CH₄ mitigation are analyzed together, in contrast to the baseline projection where they are estimated separately. This section estimates global non-CO₂ mitigation potential from rice production using DNDC, a gridded global biophysical model. Using a biophysical model improves the analysis by incorporating soil characteristics and dynamic soil processes, as well as crop-specific nutrient uptake and plant physiology.

The mitigation options included in this analysis were based on a review of the literature to identify the most promising options, while also considering data availability and the potential for modeling within DNDC. We then analyzed 26 mitigation scenarios using DNDC 9.5.¹⁰⁴ 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 CH₄ 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 CH₄ 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 decomposition, nitrification, and denitrification (Neue and Sass, 1994; Li et al., 2006).

Table 5-63 reports the 26 alternative rice management scenarios simulated using DNDC.¹⁰⁵

¹⁰⁴ Note that 38 different scenario names are reported in the outputs. Because water management practices were assumed not to affect nonirrigated rice emissions, the simulation results for options combined with continuous flooding or midseason drainage are the same for nonirrigated 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.”

¹⁰⁵ Another potential mitigation option is varietal selection toward cultivars that have lower emissions per unit of output. However, data were insufficient to represent such changes within DNDC for this study.

Table 5-63: 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
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

(continued)

Table 5-63: Alternative Rice Management Scenarios Simulated Using DNDC (continued)

Abbreviation	Scenario	Flooding	Residue Incorporation, %	Alternative Management	Fertilization
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_ninh_ib	AWD w/nitrification inhibitor	AWD	50	—	Nitrification inhibitor
awd_r50_slow_rel	AWD w/slow release rel	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 nonirrigated rice, there is no difference between scenarios with alternative water management. Thus, we refer to those scenarios for the nonirrigated rice with “base_” in front rather than “cf” or “md.”

Most of the major rice-producing countries have some mix of flood regimes in DNDC (see Table 5-64). 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 emission reductions, we compared mitigation options with 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 with baseline emissions from continuously flooded rice with conventional fertilizer (cf_r50) and with baseline emissions from rice managed using mid-season drainage with conventional fertilizer (md_r50) rather than being compared with the baseline weighted average emissions per hectare. We made this comparison 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 emission 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 results 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.

Table 5-64: Rice Management Techniques

Management Technique	Description
Rice flooding	
Continuous flooding (CF)	Rice paddy is flooded on planting date and drained 10 days before 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 before harvest date—applies only to irrigated rice
AWD	Rice paddy is initially flooded to 10 cm; water level is reduced at rate of -0.5 cm/day till to -5 cm 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	Rice paddy is flooded 40 days after planting date and drained 10 days before 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	Before first crop in rotation tillage to 20 cm depth; subsequent timesteps (following each crop in rotation) to 10 cm depth
No till	Tillage only mulches residue
Fertilizer	
Conventional	Fertilizer nitrogen applied as urea on plant date using a crop-specific rate
Ammonium sulfate	Fertilizer nitrogen 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; nitrogen is released over 90 days at a linear rate
10% reduced	Crop-specified baseline fertilizer nitrogen rate is reduced by 10% (applied as urea)
20% reduced	Crop-specified baseline fertilizer nitrogen rate is reduced by 20% (applied as urea)
30% reduced	Crop-specified baseline fertilizer nitrogen rate is reduced by 30% (applied as urea)
Auto fertilization	Fertilizer nitrogen is applied at the rate that maximizes crop yield

5.3.3.3 Technical Characteristics of Options

Rice management techniques are defined in further detail in Table 5-64.

- **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) are only applicable to irrigated systems. No water management options are available for rainfed, deepwater, or upland rice cultivation areas.

- **Technical Efficiency:** Technical efficiency was determined by the DNDC model for each country, production type, and water management combination for each mitigation option.
- **Technical Lifetime:** Technical lifetime is indefinite; no capital costs are included for which a lifetime must be defined.

5.3.3.4 Economic Characteristics of Options

- **Capital Cost:** None of the options considered for this analysis were assumed to have any capital cost.
- **Annual O&M Cost:** these recurring costs reflect the 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.

Description of the DNDC Model

For this analysis, we used a modified version of the DNDC 9.5 global database to simulate crop yields and GHG fluxes from global paddy rice cultivation systems. 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).¹⁰⁶ 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 deep water and upland cropping systems. For this study, baseline and mitigation scenario modeling was carried out for all rice-producing countries in the world that produce a substantial quantity of rice.

The FAO country-level statistics (FAOSTAT 2010) were used to establish the harvested area for rice. The total area was calculated for each country in the global database for each type and evenly distributed across all grid cells within a country in the absence of subnational information. 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, flooding, and drainage dates for irrigated rice were established based on the planting dates.

A baseline scenario was established for each country using DNDC 9.5. Rice yields and GHG fluxes (CH_4 , direct and indirect N_2O , and changes in soil organic carbon) were simulated in the 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. Results were reported for 2010 and by 5-year increments through 2030.

We adjusted results from DNDC with projected acreage of these production systems by IFPRI’s 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 the IMPACT model reflect socioeconomic 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% between 2010 and 2030, the total area dedicated to rice cultivation would decrease by 5% during the same period because of productivity improvements.

¹⁰⁶ The paddy-rice version of DNDC has been validated in many 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).

5.3.3.5 References

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5.3.4 Other Agriculture

The source category solely comprises countries that report data to the UNFCCC database. The EPA did not perform Tier 1 calculations for other agriculture sources, which include prescribed burning of savannas and field burning of agricultural residues. The EPA obtained historical values for 1990 through 2012 and held 2015 through 2050 values constant at 2012 levels for each country.

5.4 Waste Sector

This section presents the methodology used to estimate GHG emissions and mitigation potential from the following waste sector sources:

- landfilling of solid waste (CH_4)
- wastewater management (CH_4 , N_2O)
- other waste (CH_4 , N_2O) (projections only)

5.4.1 Landfills

Landfills produce CH_4 in combination with other landfill gases (LFGs) through the natural process of bacterial decomposition of organic waste under anaerobic conditions. LFGs are 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 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.

5.4.1.1 Landfill Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for landfilling of solid waste included population data from the UN (2015); gross domestic product (GDP) data from USDA (2016) or the World Bank (2017); GDP growth rates by country from OECD (2014); municipal solid waste (MSW) generation per capita and MSW landfill rates from OECD.stat (2016), Eurostat (2016) or UN Statistics Division (2016); and industrial waste generation rates from OECD (2011) or the China Statistical Yearbook (NBSC, 2015).

Emission estimates for this source are based on the IPCC First Order Decay (FOD) method using a mix of IPCC default and country-specific input data. This method assumes that the degradable organic carbon (DOC) in landfills decays under anaerobic conditions and releases CH_4 over time. Part of the CH_4 generated is oxidized or can be recovered for energy or flaring; as a result, the CH_4 actually emitted will be less than the amount generated. The 2006 IPCC Tier 1 equation used is below.

$$\text{CH}_4 \text{Emissions} = \left[\sum_x \text{CH}_4 \text{generated}_{x,T} - R_T \right] * (1 - OX_T) \quad (5.31)$$

where:

- | | | |
|---------------------------------|---|--|
| $\text{CH}_4 \text{ Emissions}$ | = | CH_4 emitted in year T , Gg |
| T | = | Inventory year |
| x | = | Waste category or type/material |
| R_T | = | Recovered CH_4 in year T , Gg |
| OX_T | = | Oxidation factor in year T (fraction) |

For further explanation regarding the methodology, please refer to Chapter 3, Solid Waste Disposal, of the 2006 *IPCC Guidelines* (IPCC, 2006).

Solid waste generation, disposal, and emissions were analyzed separately for municipal solid waste (MSW) and industrial solid waste. MSW is generally defined as waste collected by municipalities or other local authorities and typically includes household waste, garden (yard) and park waste, and commercial/institutional waste. Industrial waste includes organic, process waste generated by industry that is not included in the MSW stream. Industrial waste generation and composition vary depending on the type of industry and processes/technologies in the concerned country. Only those industrial wastes that are expected to contain DOC and fossil carbon should be considered for the purpose of estimating emissions from waste. These industries primarily include food/beverage manufacturing, wood product manufacturing, textile manufacturing, paper manufacturing, and construction and demolition waste.

Activity Data

Historical

The key activity data driving emissions from landfilling of MSW are population, the rate of solid waste generation (usually expressed in kilograms per person per day), and the rate of landfill disposal. Similarly, for industrial solid waste, the key activity data are GDP, the rate of industrial process waste generation, and the rate of landfill disposal for industrial waste. To develop the Tier 1 estimates, the analysis required historical activity data going back at least 50 years, because of the nature of landfill emissions and the FOD methodology. These data were developed using a combination of country-reported data and IPCC default assumptions.

- Population data were obtained from the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects*; custom data acquired via the website (UN, 2015). Population data for each country were obtained in 5-year increments from 1950 through 2050. Population data for the years between the reported values were linearly interpolated.
- Annual real GDP data by country from 1960 through 2050 were pulled from either the U.S. Department of Agriculture (for years 1980 through 2030) (USDA, 2016) or the World Bank (for years 1960 through 2030) (World Bank, 2017). When GDP data were not available for a country before 1980, it was back casted using either the USDA world growth rate (USDA, 2016) or the World Bank world growth rate (World Bank, 2017).
- MSW generation per capita data were available from the OECD Questionnaire on the state of the environment: municipal waste generation and treatment (OECD.stat, 2016); Eurostat, municipal waste generation and treatment (Eurostat, 2016); and the United Nations Statistics Division (UNSD), environmental statistics database: municipal waste collected (UNSD, 2016). These data provide country-reported information for 75 countries from 1990 through 2015. Most countries do not have data reported for every year, so missing values were linearly interpolated. To complete the time series back to 1960, we assumed a constant per capita value based on the last reported year available in the country-reported historical data. For countries with no reported data, IPCC default values for the year 2000, were used to specify waste generation per capita, and the rest of the historical time series similarly assumed constant waste generation historically. IPCC default values were specified for regions and mapped to individual countries (IPCC Table 2.1).
- Total annual waste generation was calculated as the product of population and waste per capita.
- MSW composition was based on IPCC default values specified by region, which were mapped to individual countries (IPCC Table 2.3). The composition does not vary by year.
- MSW landfill rate data were taken from the OECD Questionnaire on the state of the environment: municipal waste generation and treatment (OECD.stat, 2016) and Eurostat, municipal waste generation and treatment (Eurostat, 2016). These data provide country-reported information for 43 countries over the period 1990 through 2015. Most countries do not have data reported for every year, so missing values were linearly interpolated. To complete the time series back to 1960, the EPA assumed the same disposal

rate as the last year of reported data. For countries with no reported data, the year 2000 IPCC default value was selected as the landfill disposal rate for all years. IPCC default values were specified for regions and mapped to individual countries (IPCC Table 2.1).

- Industrial waste generation data from key industrial sources of organic process waste were available from OECD, Environment Statistics Database, waste generation by sector (OECD, 2011). Data for China were obtained from the China Statistical Yearbook (NBSC, 2015). These data provide tons of industrial waste for key contributing industries, including food, textiles, wood, paper, and construction and demolition, for 32 countries from 1990 through 2012. Most countries have data for a subset of years, so missing values were linearly interpolated.
- Per IPCC guidance, overall average industrial waste generation rates by country are based on reported data. These rates do not vary over time because of limitations in the country-reported data. For countries with no reported industrial waste data, input values were assigned based on similar or proximate countries for which data are reported.
- Total annual industrial waste generation was calculated as the product of the generation rate and annual GDP.
- Industrial waste composition was estimated as the proportion coming from each key industrial waste source (i.e., food, textiles, wood, paper, and construction and demolition). The quantity of waste by source category is required because the DOC values in the emission calculations vary by material. This composition does not vary over time because of limitations in the country-reported data. For countries with no reported industrial waste composition data, input values were assigned based on similar or proximate countries for which data are reported.
- Industrial waste landfill rates were from country-reported data. When country-reported data were not available, industrial landfill rates were assumed to be half of the country's reported MSW landfill rate.

Projected

- Consistent with historical population data, the population data projection relies on the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects*, custom data acquired via the website (UN, 2015). Population data for each country were obtained in 5-year increments from 1950 through 2050. Populations for years between the reported values were linearly interpolated.
- GDP data were projected beyond 2030 using the OECD country growth rates for available countries. When country-specific growth rates were not available, the OECD world growth rate was used (OECD, 2014).
- MSW generation per capita is assumed to be constant and equal to the most recently available country-reported or IPCC default data from either the last country-reported value or the IPCC default 2000 value based on the annual percentage change in GDP per capita. Total future MSW was based on the product of future population and the future waste generation rate.
- MSW landfill rates were assumed to be the same as the most recent year of country-reported data. When no country-reported data were available, the IPCC default value was used.
- Because the average industrial waste generation rate by country does not vary over time, it was assumed constant for projected years. Total future industrial waste generation is the product of future GDP and the industrial waste generation rate.
- Projected industrial waste landfill rates were assumed to be half of the projected MSW landfill rates.

Emission Factors

Historical and Projected

The analysis used IPCC Tier 1 emission factors, including the following assumptions:

- DOC by waste material was obtained from *2006 IPCC Guidelines* Table 2.4 for MSW and Table 2.5 for industrial waste.
- The fraction of DOC dissimilated (DOC_f) is a constant from *2006 IPCC Guidelines* (0.5) for all materials and countries.
- CH_4 generation rates by waste material and climatic zone were obtained from *2006 IPCC Guidelines* Table 3.3.
- Oxidation (OX) and recovery (R) were assumed to equal zero, per IPCC guidance.
- Default values from *2006 IPCC Guidelines* Table 3.1 and the IPCC Waste Model were used for estimated distribution of landfill types used to manage landfilled waste (i.e., managed or unmanaged, deep or shallow, and uncategorized).

Emission Reductions in Baseline Scenario

No emission reductions assumptions were applied in the methodology to estimate emissions from this source. However, emission reductions are included to the extent they are reflected in country-reported data.

Uncertainty

Uncertainties in the emission estimates are directly related to the quality and availability of the input data used to derive the emissions. As noted in *2006 IPCC Guidelines* (2006), there are several key areas of uncertainty to consider in the emission estimates, including the following:

- MSW generation subject to landfilling is based on the country's total population. To the extent that total population does not reflect the population for which waste is collected, the analysis may overstate waste generation.
- The analysis relies on *2006 IPCC Guidelines* default assumptions to describe the CH_4 correction factor (MCF) for each type of landfill in the model and the associated mix of different types of landfills used to manage MSW. These characteristics are critical in determining emissions from a landfill; however, the default values do not vary by country or over time. This introduces significant uncertainty, particularly at the level of the individual country (versus global), because the default will not reflect the characteristics of each country's landfills. It is not clear in which direction this uncertainty biases the results.
- Similarly, the composition of materials in MSW is based on broad IPCC default assumptions. In reality, waste composition varies widely even within countries (e.g., between urban and rural populations, between households with different incomes) as well as between countries. It is not clear in which direction this uncertainty biases the results.
- Per IPCC Tier 1 guidance, the Tier 1 estimates do not include CH_4 oxidation or recovery for flaring/energy, which may result in overstated emissions.
- Industrial solid waste generation data for key industries that produce waste with DOC are based on limited country-reported information. In addition, there are no country-reported data describing the management of industrial solid waste. These limited data require assumptions (e.g., mapping data from one country to multiple countries and using MSW landfilling rates as proxy) that introduce significant uncertainty into the industrial waste estimates. An additional consideration is that it is not clear what is included in the available industrial waste generation data. The analysis would ideally be limited to the process waste from these industries (e.g., food waste and paper waste), rather than also including material such as office waste, which is captured by the MSW stream. To the extent that the OECD industrial waste data are not limited to process waste, the analysis likely overstates industrial waste generation.

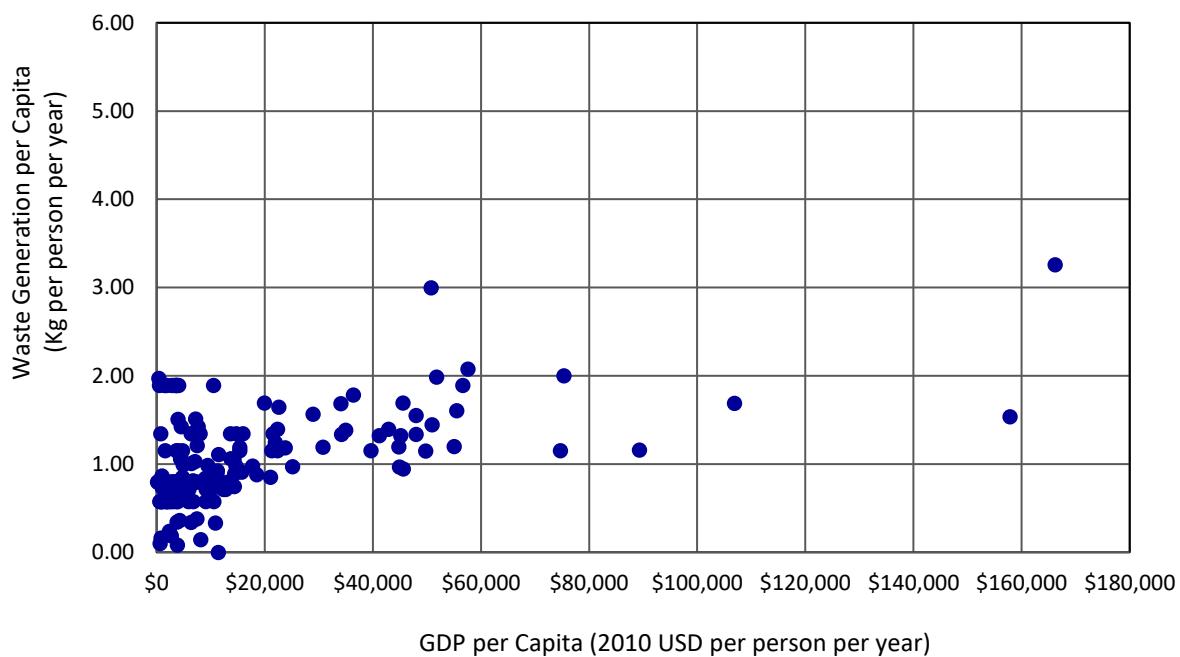
A Note on Per Capita Waste Generation

As described above, the analysis assumed constant per capita waste generation based on the most recently available country-reported or IPCC default data to complete the annual forecast and backcast that underlie the Tier 1 approach. To the degree that per capita waste generation changes over time based on economic development, generally, this approach may overstate historical generation and underestimate future estimates of per capita waste generation at the country level. EPA also considered approaches to forecast per capita waste generation based on a quantified relationship to GDP per capita. However, the empirical relationship between per capita generation and economic indicators such as GDP per capita is not clear.

The literature generally agrees that GDP or income and waste generation are linked, but factors such as the degree of urbanization and changes in waste management policies and infrastructure, which are by-products of growth, complicate the relationship. For instance, “after 20 years of rapid economic growth through 1997, the government of Taiwan enforced aggressive MSW management practices, which contributed to a large reduction in the per capita MSW generation from 1.14 kg day⁻¹ in 1997 to 0.81 kg day⁻¹ in 2002, even though the economy continued to grow” (Kawai and Tasaki, 2016).

Figure 5-4 below presents the relationship between GDP per capita and waste generation per capita for 2015 from EPA’s Tier 1 methodology for 191 countries.

Figure 5-4: Waste Generation vs GDP (Per Capita, 2015)



Based on these data, countries with GDP per capita below about \$20,000 (USD 2010) demonstrate more variability in per capita waste generation. Above this threshold, countries are in a relatively tight range between 1 and 2 kilograms of solid waste per person annually, regardless of GDP per capita.

Absent a more rigorous understanding of the relationship between these indicators and how the relationship varies based on a given country’s current development status and prospects for future growth, the EPA judges that it is reasonable to assume a constant value for the forecast. Using this approach, the EPA’s Tier 1 landfill model estimates a total of 2.18 billion tonnes of waste generated in 2025, which is consistent with other widely cited international forecasts (World Bank, 2012).

5.4.1.2 Landfill Mitigation Options Considered

Model Facilities

This analysis considers abatement measures' impacts on three model facilities representing the solid waste management alternatives with different levels of CH₄-generating capacity:

- **Open dump sites:** Defined as solid waste disposal facilities where the waste is left uncompacted and without cover.
- **Basic landfills (also referred to as managed dump sites):** Defined as solid waste disposal facilities where the waste is compacted and covered but there are no additional engineered systems.
- **Engineered sanitary landfills:** Defined as facilities that include waste compaction and cover and are designed and constructed with gas and leachate collection systems.

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 L₀ (CH₄ 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 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 of waste over a smaller area and at increased depths of between 40 and 50 feet. Facility CH₄ 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 5-65 summarizes the standardized model facility assumptions.

Table 5-65: Model Facility Assumptions for International LFG Mitigation Options

Facility Type	No. Years Open	Annual Waste Acceptance Rate (tonnes/yr)	Project Design Area (Acres)	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 L₀ (CH₄ generation potential) and k constant (decay rate) values, the two key parameters in the first order decay model, which was used to estimate LFG generation. Both parameters were calculated based on the composition of the waste being landfilled, which was determined by the country-specific socioeconomic conditions, consumption patterns, and waste management practices. Therefore, the CH₄ generation results and, consequently, the amount of CH₄ potentially mitigated by each LFG 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 CH₄ generation potential of waste (L₀) for 16 countries that included at least one country within 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, the EPA's voluntary program, the MSW Decision Support Tool (DST), and other peer-reviewed literature.

Second, we used expert judgment, taking into consideration trends of socioeconomic and technological development to associate countries with other countries for which we have CH₄ generation data (e.g., we have CH₄ generation data for Jordan and considered that Algeria, Egypt, and South Africa have similar socioeconomic and technological conditions). Alternatively, we have CH₄ 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 5-66 presents the data used to characterize the model facilities for specific countries identified for this analysis.

Table 5-66: CH₄ Generation Factors by Country

Country	Region ^a	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

^aCCSA = Central & South America

Sources: WB—World Bank Studies by Country; LMOP—EPA's LMOP country-specific LFG models; MSW DST—decision support model; and Zhu et al. (2007).

The international assessment of other OECD countries assumed waste management practices and landfill designs similar to those in the United States. For this reason, we leveraged 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.

5.4.1.3 Mitigation Options Considered

This analysis considers two types of abatement measures: mitigation technologies and diversion alternatives. Mitigation technologies represent add-on technologies that can be applied to one or more landfill types described above (i.e., open dump, basic landfill, engineered landfill) intended to capture and destroy the CH₄. Diverting

organic waste from the landfill for alternative uses is the second approach to reduce the quantity of LFG generated at existing landfills.

Mitigation Technologies

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. These systems prevent the migration of CH₄ to on-site structures and adjacent property and prevent the release of non-CH₄ organic compounds to the atmosphere. Flares ignite and burn LFG. 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 (EPA, 2010).

- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumed a collection efficiency of 75% for basic landfills and of 85% for engineered landfills and a flaring efficiency of 98%.
- **Technical Lifetime:** 15 years
- **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 EPA Landfill Methane Outreach Program (LMOP) Project Cost Estimation Model.
- **Annual 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 year¹⁰⁷ (EPA, 2010), assuming an electricity price of 7 cents/kWh and consumption rate of 0.002 kWh per ft³.
- **Annual Benefits:** No economic benefits (energy production) are associated with this option.

LFG Collection for Electricity Generation

Converting LFG to electricity offers a potentially cost-effective way to use the gas being generated by the landfill. This option requires an 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.

- **Applicability:** This option applies to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumed a collection efficiency of 75% for basic landfills and 85% for engineered landfills and combustion efficiency of 98%.
- **Technical Lifetime:** 15 years
- **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 EPA LMOP Project Cost Estimation Model, which is available at EPA's LMOP web page (see Table 5-67).
- **Annual O&M Cost:** Annual O&M costs are between \$130 and \$380 per kilowatt of capacity.
- **Annual Benefits:** Annual revenues are derived from the sale of electricity.

¹⁰⁷ For this analysis, we assumed an electricity price of 7.5 cents/kWh and an energy consumption rate of 0.002 kWh/ft³.

Table 5-67: 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

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.¹⁰⁸ Although little condensate removal and filtration is needed, combustion equipment might need slight modifications to run with LFG (EPA, 2010). However, these modification costs are not considered part of the technology costs.

- **Applicability:** This option is available to all basic landfills and engineered landfills.
- **Technical Efficiency:** This analysis assumed 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
- **Capital Cost:**¹⁰⁹ Costs 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).
- **Annual Cost:** Annual O&M costs include the cost of electricity and maintenance of the filters, compressors, and dehydrators. The electricity costs were 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/ft³. Non-energy-related O&M costs were scaled to LFG project volumes assuming a cost of \$0.0014/ft³.
- **Annual 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.

Enhanced Oxidation Systems

Enhanced oxidation systems are considered mitigation technologies that exploit the propensity of some naturally occurring bacteria to oxidize CH₄.¹¹⁰ By providing optimum conditions for microbial habitation and efficiently routing LFGs to where they are cultivated, a number of bio-based systems, passively or actively vented biofilters, and biowindows have been developed that can alone, or with gas collection, mitigate landfill CH₄ emissions.

¹⁰⁸ Other direct use applications include use in infrared heaters, greenhouses, artisan studios, leachate evaporation, and biofuel production.

¹⁰⁹ 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 (EPA, 2010).

¹¹⁰ Oxidation of methane entails mixing the gas (CH₄) with oxygen and converting the CH₄ to CO₂ and water.

- **Applicability:** This option applies to basic landfills and engineered landfills.
- **Technical Efficiency:** This option analysis assumed a reduction efficiency of 44% of the remaining 15% of CH₄ not collected by LFG collection system (Weitz, 2011).
- **Technical Lifetime:** 50 years
- **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/yd³ for earth moving, a compost price of \$5/tonne,¹¹¹ 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.

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). The following diversion alternatives were considered for this analysis:

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 used in agriculture as soil conditioner.

- **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 CH₄ potential.
- **Technical Lifetime:** 15 years
- **Capital Cost:** 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 MSW DST (MSW DST Documentation), which presents this cost for 100 tons/day facilities producing marketable high-quality compost products.
- **Annual Cost:** The O&M cost of the windrow composting facility includes the labor, overhead, fuel, electricity, and equipment maintenance costs.¹¹² This analysis assumes an O&M cost of \$19/tonne-yr (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 assumed that 80% of the incoming organic waste is converted to marketable compost product.

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 CH₄ and CO₂ in the biogasification step. The biogas can be recovered and used to generate energy. This analysis considers AD that produces electricity using a gas engine, which is the most common product. A small amount of CH₄ may be

¹¹¹ The compost price assumes a weight by volume of 0.32 tonnes/yd³ (DST Model Documentation).

¹¹² 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).

released as fugitive emissions during the digestion process. This analysis assumes CH₄ emissions of 1 to 2 g/kg of waste (dry weight) as reported in IPCC (2006).

- **Applicability:** This option assumes removal of wood, paper, and food waste.
- **Technical Efficiency:** This analysis assumed a capture efficiency of 75% and a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years
- **Capital Cost:** 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 obtained from Eunomia (2008), which describes this cost for facilities of 20,000 to 30,000 tonnes/yr in the United Kingdom (U.K.).
- **Annual Cost:** The O&M cost 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 U.K. facilities.
- **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 was assumed to be 75% of total value, and the biogas composition was assumed to be 60/40% CH₄/CO₂ 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).

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 (e.g., 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 LFG, small amounts of leachate, and a reduced settlement of the landfill body).

- **Applicability:** This option applies to all landfill types,
- **Technical Efficiency:** This analysis assumed a reduction efficiency of 95%.
- **Technical Lifetime:** 20 years
- **Capital Cost:** The plant's capital cost includes the cost of land, facility, equipment, and air pollution control and monitoring devices. The analysis assumed a capital cost of \$15 million based on a reported facility cost of \$244/design tonne (reported as £150 British pounds/tonne) obtained from Eunomia (2008). Costs are reported for a 60,000 tonne/yr facility in the U.K.
- **Annual O&M Costs:** The O&M cost of the MBT facility was \$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).
- **Annual Benefits:** Annual revenues from the sale of refuse-derived fuel (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 was 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/tonne¹¹³ for nonferrous metals, and \$25/tonne for glass were used to estimate the revenues from recyclables sale.

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 considered the separation process.

- **Applicability:** This option applies to the entire waste stream.
- **Technical Efficiency:** This analysis assumed a reduction efficiency of 95% of potential CH₄.
- **Technical Lifetime:** 20 years
- **Capital Costs.** The capital cost for this option is \$35 million in (2010 USD). It consists of construction, engineering, and equipment costs. It assumes a handling capacity of 100,000 tonnes of waste per year. This analysis relied 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 was based on reported operating costs used in the 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 paper¹¹⁴—\$140/tonne; scrap metals¹¹⁵—\$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.

Waste to Energy (WTE)

WTE is a combustion process; thus, its main emissions include CO₂, CO, NO_x, and non-CH₄ VOCs. 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. This analysis considers WTE using mass-burn incineration and electricity recovery, which is the most common WTE design. Representative CH₄ emissions of 0.2 to 60 kg/Gg of waste (wet weight) and N₂O emissions of 41 to 56 g/ton of waste (wet weight) were obtained from IPCC (2006).

- **Applicability:** This option applies to the entire waste stream.
- **Technical Efficiency:** This analysis assumed a reduction efficiency of 100%.
- **Technical Lifetime:** 20 years
- **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

¹¹³ Price obtained from MetalPrices.com at http://www.metalprices.com/FreeSite/metals/al_scrap/al_scrap.asp#Tables.

¹¹⁴ Prices were obtained from: <http://www.recycle.cc/freepapr.htm>.

¹¹⁵ 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/.

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 U.K.

- **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. They do not include the cost for disposing of the combustion residue and spray dryer residue. The cost is based on an annual O&M cost of \$41/tonne/year. 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) was 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:** Revenues from electricity sales represent the annual benefits for this option. Electricity is generated by recovering heat from combusting waste. The recovery of the heat is inefficient, which 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 was used to estimate the revenues.

5.4.1.4 Technical and Economic Characteristics Summary

Table 5-68 summarizes the engineering and costs assumptions for mitigation options considered for MSW landfills.

Table 5-68: Summary of the Engineering and Cost Assumptions for Mitigation Options 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 measure's ability to mitigate/avoid CH₄ generation. However, this does not reflect the total mitigation potential.

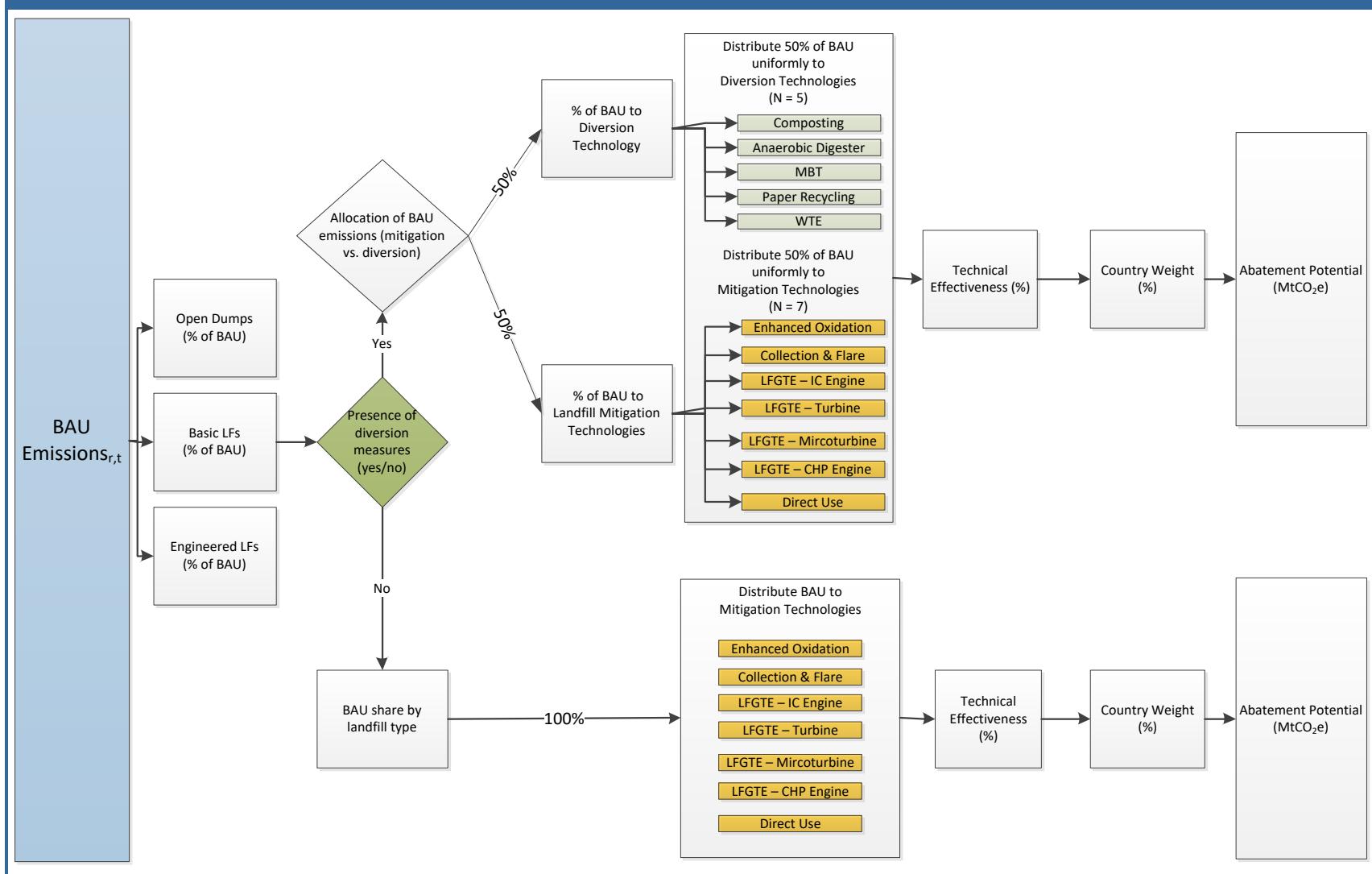
5.4.1.5 Sector-Level Trends and Considerations

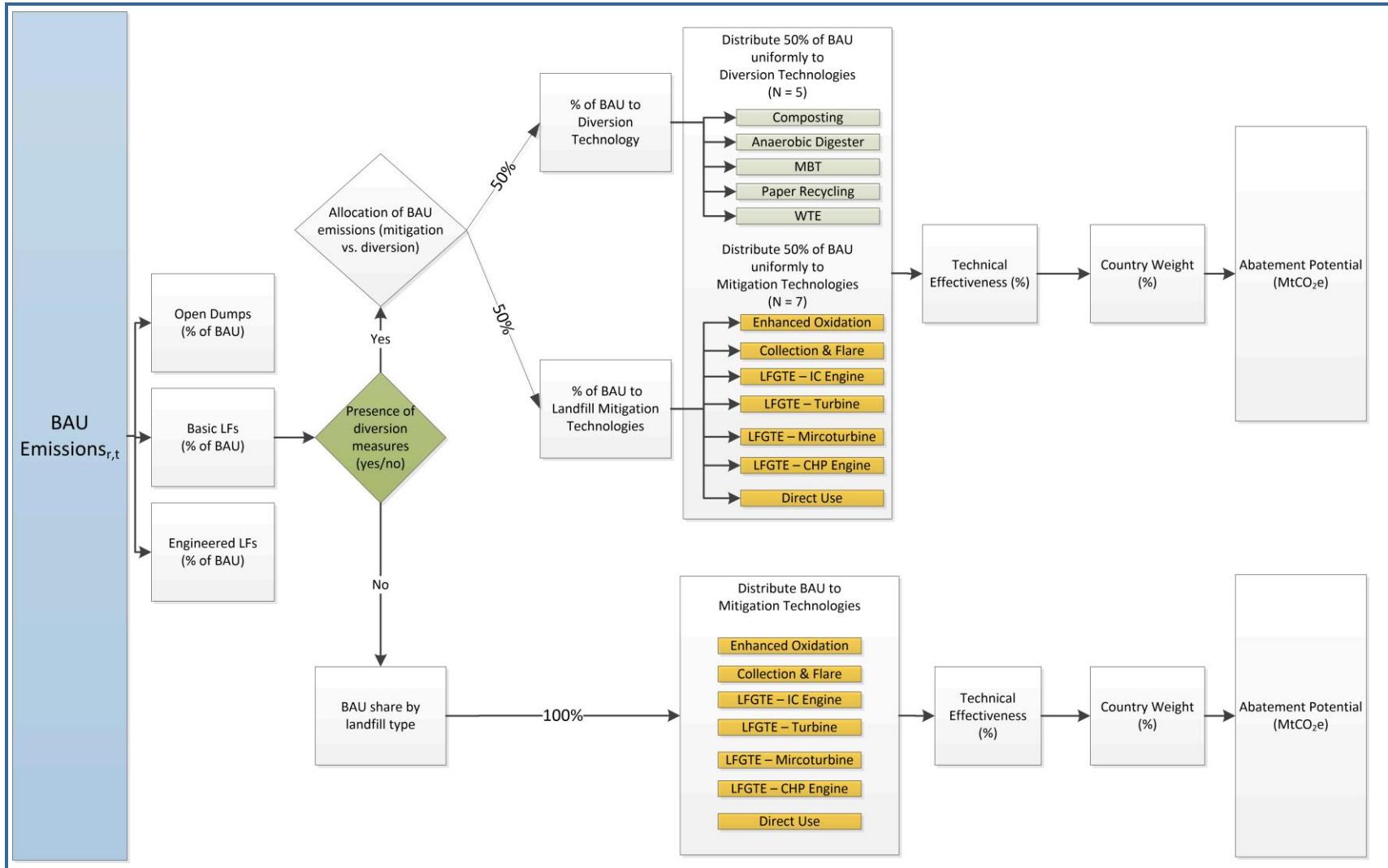
It is important to note that depending on the scenario considered in the model, diversion options may or may not be included. If diversion options are considered, BAU emissions (indexed by facility type) are uniformly distributed by the total number of technologies ($N = 12$). If diversion options are omitted, BAU emissions are distributed by the number of landfill-based mitigation technologies ($N = 7$) (see Figure 5-5).

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 this section (i.e., open dump, basic landfill, and engineered landfill). Table 5-69 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.

For emerging economies and developing countries, the analysis assumed 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, EPA's LMOP program, and the GMI.

Figure 5-5: Conceptual Model for Estimating Mitigation Potential in the MSW Landfill Sector





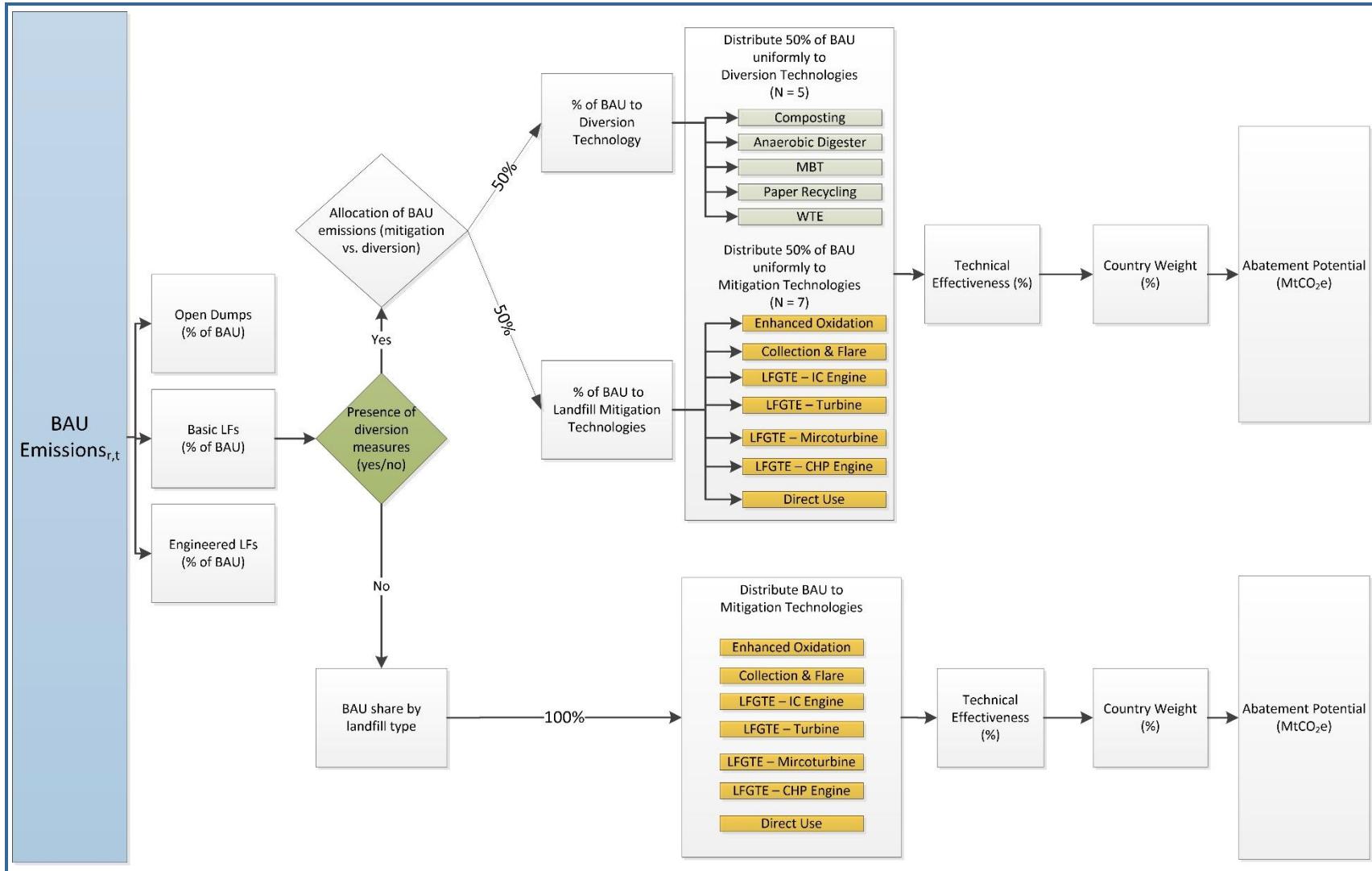


Table 5-69: Model Facilities Share of BAU Emissions: 2010–2030

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 EPA (2009, 2011).

5.4.1.6 References

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5.4.2 Wastewater Management

Wastewater originates from a variety of residential, commercial, and industrial sources and may be treated on site (uncollected), seweried to a centralized plant (collected), or disposed of untreated nearby or via an outfall. Domestic and industrial wastewater treatment activities can result in deliberate venting and fugitive emissions of CH₄. In addition, domestic wastewater is a source of N₂O emissions. CH₄ 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 CH₄ 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. Industrial wastewater can also be treated anaerobically, with significant CH₄ being emitted from those industries with high organic loadings in their wastewater stream, such as food processing and pulp and paper facilities (EPA, 2012).

5.4.2.1 Wastewater Projections Methodology

UNFCCC-reported, country-specific estimates were used for historical emission estimates in this source category, when available. For those countries with country-reported emission estimates, emission projections were estimated from the most recent country-reported data through 2050 using growth rates calculated by the Tier 1 methodology. For countries that do not have country-reported historical data, Tier 1-calculated emission estimates were used for the full time series from 1990 through 2050 (see Section 3.3, Generating the Composite Emission Projections, for additional information). Activity data for wastewater management included population data from the UN (2015), urban population data from the UN (2014), percentage of the population with wastewater collection and treatment from the UN Statistics Division (2016) and per capita protein generation from FAO (2016). While country-reported estimates include both domestic and industrial wastewater, the emission estimates calculated using Tier 1 methodology only include domestic wastewater.¹¹⁶

Methane from Wastewater Treatment/Discharge

The general equation to estimate CH₄ emissions from domestic wastewater is as follows:

$$CH_4 \text{ Emissions} = [\sum_{i,j} (U_i \cdot T_{i,j} \cdot EF_j)] \cdot (TOW - S) - R \quad (5.32)$$

where:

<i>CH₄ Emissions</i>	= CH ₄ emitted in year <i>T</i> , kg CH ₄ /yr
<i>TOW</i>	= Total organics in wastewater in year, kg biochemical oxygen demand (BOD)/yr
<i>S</i>	= Organic component removed as sludge, kg BOD/yr (<i>S</i> =0)
<i>U_i</i>	= Fraction of population in income group, <i>i</i>
<i>T_{i,j}</i>	= Degree of utilization of each treatment pathway, <i>j</i> , for each income group, <i>i</i>
<i>i</i>	= Income group: rural, urban high-income, urban low-income
<i>j</i>	= Wastewater treatment/discharge pathways
<i>EF_j</i>	= Methane emission factor, kg CH ₄ / kg BOD
<i>R</i>	= Quantity of methane recovered, kg CH ₄ /yr

Key drivers of wastewater emissions include the quantity of degradable organic material in the wastewater and the type of treatment system used. Treatment systems or discharge pathways that provide anaerobic environments will generally produce CH₄, whereas systems that provide aerobic environments will normally produce little or no CH₄. BOD is used to measure the organic component of domestic wastewater. The total

¹¹⁶ While industrial wastewater emissions were not explicitly estimated in this report, some countries report industrial wastewater emissions within this source category. In these cases, this source category includes these emissions.

quantity of domestic BOD in the base year and subsequent years is driven by changes in population and per capita BOD generation.

Nitrous Oxide Emissions from Wastewater

The general equation to estimate N₂O emissions from domestic wastewater is as follows:

$$N_2O = N_{\text{effluent}} * EF_{\text{Effluent}} * (44/28) \quad (5.33)$$

where:

N_2O Emissions = N₂O emission, kg N₂O/yr

N = Nitrogen (N) in the effluent discharged into aquatic environments, kg N/yr

EF = Emission factor for N₂O emission, kg N₂O-N / kg N

The factor 44/28 is the conversion of kg N₂O-N into kg N₂O.

Activity Data

Methane from Wastewater Treatment/Discharge

Historical

- Annual total population data by country in 5-year increments from 1950 through 2015 were obtained from the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects* (UN, 2015). Population data for years between the reported values were linearly interpolated.
- The annual percentage of urban population was obtained from *The 2014 Revision* (UN, 2014). Urban population is split into high- and low-income urban populations based on IPCC default proportions, provided for a sample of countries and regions (see Table 6.5 of the *2006 IPCC Guidelines*) (IPCC, 2006).
- The percentage of the population with wastewater collection and treatment was obtained from the United Nations Statistics Division, environmental statistics database: percentage of population with wastewater collection and treatment (UNSD, 2016). These data provide country-reported information for 58 countries over the period 1990 through 2009, although most countries do not have data reported for every year; missing values were linearly interpolated. These data provide a basis for determining the percentage of wastewater that is (1) collected and treated, (2) collected but untreated, and (3) uncollected. For countries that do not have reported data, the EPA used the IPCC default assumptions for the percentage utilization of these pathways, based on Table 6.5 of the *2006 IPCC Guidelines* (IPCC, 2006). Values do not vary by year for countries using IPCC default values.
- The total quantity of organics in wastewater is calculated as the product of population and BOD per person. IPCC default BOD values were used. Countries without IPCC default values were assigned values based on a nearby country or the associated region (see Table 6.4 of the *2006 IPCC Guidelines*) (IPCC, 2006).
- The total quantity of BOD in wastewater, by collection/treatment path and urban/rural designation, was estimated based on total BOD, the fraction of population in each income class, and proportion of wastewater in each discharge pathway, per above.

Projected

- Annual total population data by country in 5-year increments from 2016 through 2050 were obtained from the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects* (UN, 2015). Population data for years between the reported values were linearly interpolated.

- For all projected activity data, the EPA assumed the last year of country-reported data, if available, or otherwise relied on the IPCC defaults, which do not change over time.

Nitrous Oxide Emissions from Wastewater

The activity data needed to estimate N₂O emissions include the nitrogen content in the wastewater effluent, country population, and average annual per capita protein generation.

Historical

- Annual total population data by country in 5-year increments from 1950 through 2015 were obtained from the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects* (UN, 2015). Population data for years between the reported values were linearly interpolated.
- Per capita protein generation, which consists of intake (consumption), was obtained for 1990 through 2011 for 162 countries from FAO (2016). Missing values over this period were linearly interpolated. Countries for which no data are available were mapped to proximate country data.

Projected

- Annual total population data by country in 5-year increments from 2016 through 2050 were obtained from the United Nations Department of Economic and Social Affairs, Population Division, *World Population Prospects* (UN, 2015). Population data for years between the reported values were linearly interpolated.
- Projected per capita protein generation was assumed to be equal to the last year of country-reported data for all future years, 2011 through 2050.

Emission Factors

Methane from Wastewater Treatment/Discharge

Historical and Projected

The analysis used IPCC Tier 1 emission factors, including the following assumptions:

- Maximum CH₄ production capacity (kg CH₄/kg BOD) is the IPCC default emission factor (see Section 6.2 of the *2006 IPCC Guidelines*), which was further adjusted based on the specific discharge pathway in use based on IPCC default MCF (see Table 6.3 of the *2006 IPCC Guidelines*) (IPCC, 2006).
- IPCC default MCFs are provided for specific wastewater treatment approaches, which are more detailed than the categories of collected-treated, collected-untreated, and uncollected (e.g., septic, sewer, latrine). The EPA developed weighted average MCFs to represent the three categories in the analysis. Using these three categories enabled the analysis to leverage country-reported wastewater management data.

Nitrous Oxide Emissions from Wastewater

Historical and Projected

The analysis used IPCC (2006) Tier 1 emission factors, including the following assumptions:

- fraction N in protein (kg N/kg protein) based on IPCC 6.3.3
- fraction of nonconsumption protein for developed countries based on IPCC 6.3.1.3 and for developing countries based on IPCC 6.3.1.3
- fraction of industrial and commercial co-discharged protein based on IPCC 6.3.1.3
- N removed with sludge based on IPCC Ch. 6
- emission factor (kg N₂O/kg N) based on IPCC 6.3.1.2
- conversion factor to convert kg N₂O-N to kg N₂O based on IPCC Ch. 6

Emission Reductions in Baseline Scenario

CH₄ emissions from wastewater can be reduced through improved wastewater treatment practices, including reducing the amount of organic waste anaerobically digested and flaring or using CH₄ from anaerobic digesters for cogeneration or other beneficial reuse. Such emission reduction activities are not widespread, so they are not explicitly included in these estimates. The estimates do not account for possible future modernization of domestic wastewater handling that may see a shift to aerobic treatments and the implementation of CH₄ capture from anaerobic digesters that would result in a reduction of emissions.

Uncertainty

For domestic wastewater, the primary uncertainties lie in specifying the annual utilization of different wastewater management practices and the associated IPCC default emission factors for those practices. In addition, large uncertainties are associated with the IPCC default emission factors for N₂O from effluent.

5.4.2.2 Wastewater Mitigation Options Considered

This analysis focused on domestic wastewater treatment and implementation of abatement measures aimed at reducing CH₄ emissions, which can be mitigated through investment in infrastructure and/or equipment. Conversely, there are no proven and reliable technologies for mitigating N₂O emissions. Mitigation steps to limit N₂O emissions from wastewater treatment require technical expertise and experience rather than an engineered solution; thus, they fall outside the scope of an engineered cost analysis. This analysis considers abatement measures that may be applied to one of five existing wastewater treatment systems currently being used 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 of the sanitation ladder. Figure 5-6 presents the five baseline scenarios for the existing status quo.

Figure 5-6: Five Existing Scenarios Evaluated for Given Wastewater Discharge Pathways Based on Technology Level, Treatment Alternative, and Collection Method

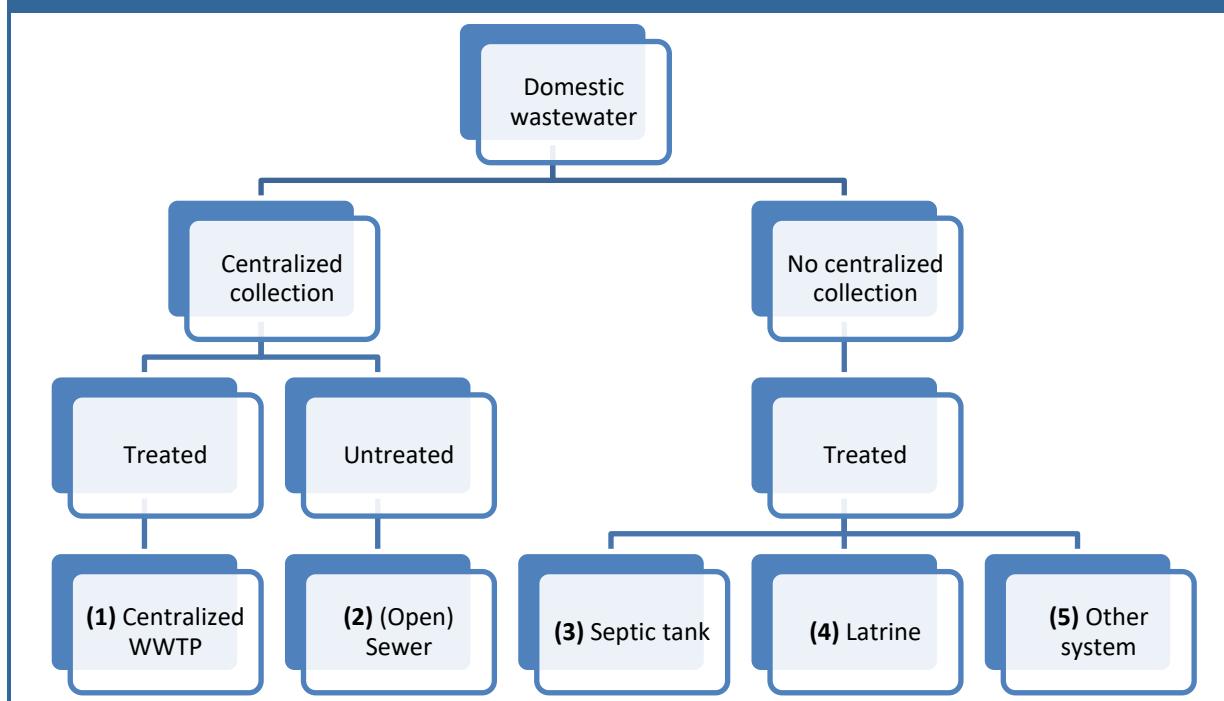


Table 5-70 compares the three abatement alternatives for an example population of 400,000 people, population density of 3,000/km², and wastewater generation rate of 340 L/person/day.

Table 5-70: Mitigation Options for the Wastewater Sector

Abatement Option	Total Installed Capital Cost (2010 10 ⁶ USD)	Annual O&M Cost (2010 10 ⁶ 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%

CH₄ Mitigation Technology for Existing Decentralized Treatment

This section characterizes the reduction in CH₄ emissions by adding a collection system and centralized treatment facility in developing countries where the current practice is decentralized wastewater 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 CH₄. The construction and implementation of a collection system and subsequent treatment at a centralized facility would significantly reduce CH₄ 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 large distances 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.

- **Applicability:** This option applies to all scenarios having no existing centralized collection system.
- **Technical Efficiency:** This analysis assumed an initial collection efficiency of 60%, which increases by 10% each year, because of an assumed improvement in technical efficiency.
- **Technical Lifetime:** 50 years
- **Capital Cost:** We used the cost estimation model Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR) (Finney and Gearheart, 2004) 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/km²) = 360.54 × D_p^{-0.844}, where D_p is population density in (persons/km²).

- **Annual O&M Cost:** Annual O&M costs for collection systems were scaled from the capital cost and assumed to be a factor of $0.028 \times$ initial capital cost, which for this case gives the following cost curve, based on population density: O&M cost (\$MM/km²) = $10.095 \times D_p^{-0.844}$.
- **Annual Benefits:** No benefits are associated with this option.

Aerobic Wastewater Treatment Plant (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. We provide a brief summary of each of these classifications:

- **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.
- **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.
- **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.
- **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.
- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumed an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.
- **Capital Cost:** Capital costs were estimated using EPA's cost curves detailing the construction costs of publicly owned wastewater treatment facilities (EPA, 1980). The cost curves in EPA (1980) are based on actual winning bids for treatment plants, 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 m³/day.
- **Annual 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's cost curves (updated to 2010 dollars) provide the following cost curve for an aerobic WWTP, based on the flow rate: $0.0002 \times Q^{0.8517}$.
- **Annual Benefits:** None.

CH₄ Mitigation Technology for Existing Collection System without Treatment

This section characterizes the reduction in CH₄ emissions for the existing condition of a centralized collection system without a treatment facility. 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.

- **Applicability:** This option applies to all conditions when new WWTPs are constructed.
- **Technical Efficiency:** This analysis assumed an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years.
- **Capital Cost:** Capital costs were estimated using EPA's 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 m³/day.
- **Annual 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. The costs were based on a detailed equipment and materials database that uses 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.

CH₄ Mitigation Technology for Existing Centralized Aerobic WWTPs

Anaerobic Biomass Digester with CH₄ Collection

The top of the technology ladder evaluated assumes that 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 CH₄ 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 CH₄. Anaerobic digesters are large covered tanks that are heated to optimize the CH₄-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% CH₄ and the 30 to 40% CO₂, 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.

- **Applicability:** This option applies to all existing WWTP types.
- **Technical Efficiency:** This analysis assumed an initial collection efficiency of 60%, which increases by 10% each year.
- **Technical Lifetime:** 20 years
- **Capital Cost:** Costs were derived from EPA's 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 m³/day.
- **Annual 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) = $0.00042 \times Q^{0.7939}$.

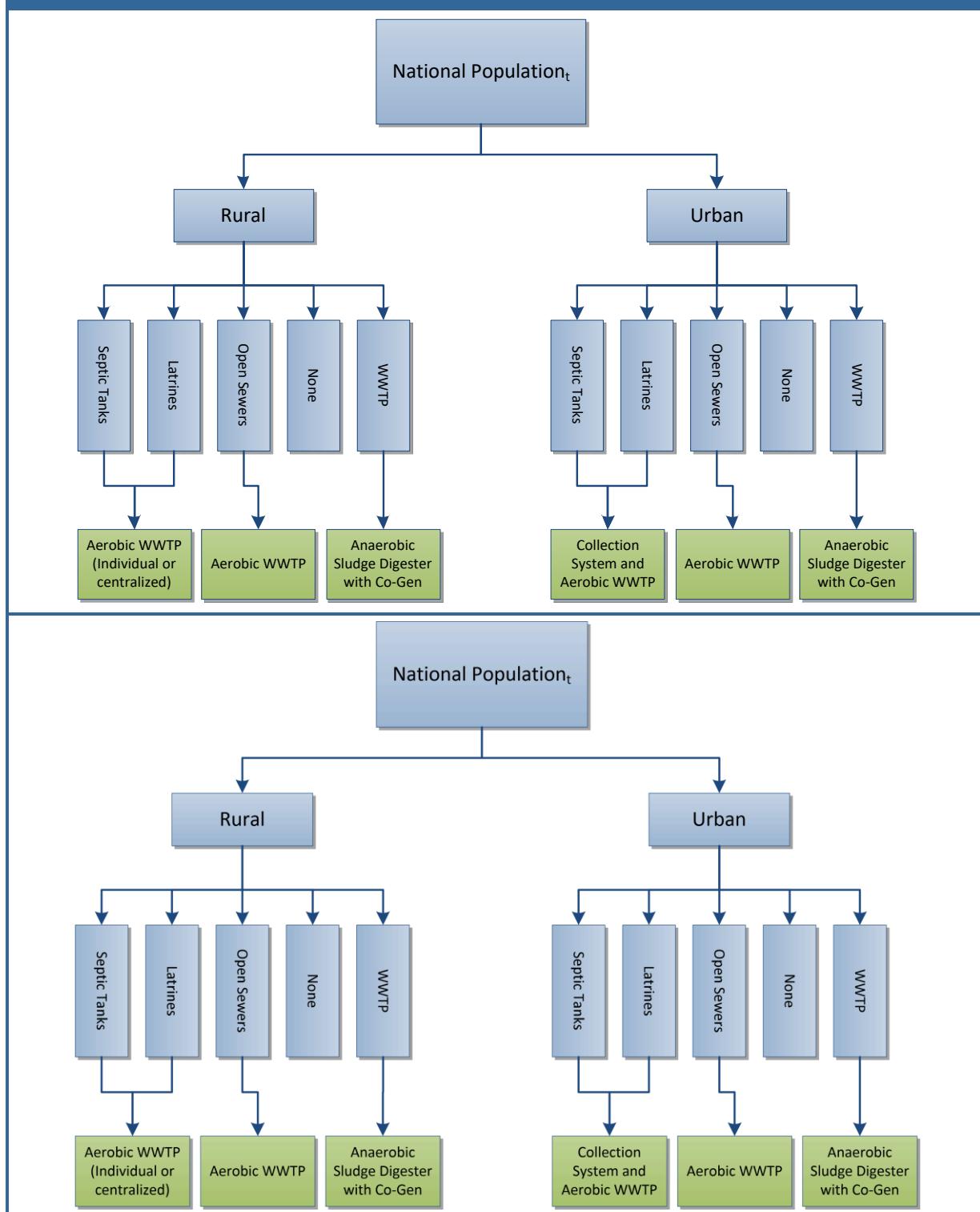
- **Annual Benefits:** Stabilized sludge can be land applied as fertilizer. The cogeneration option provides electricity. Flared gas can be used elsewhere at the plant to reduce overall energy requirements.

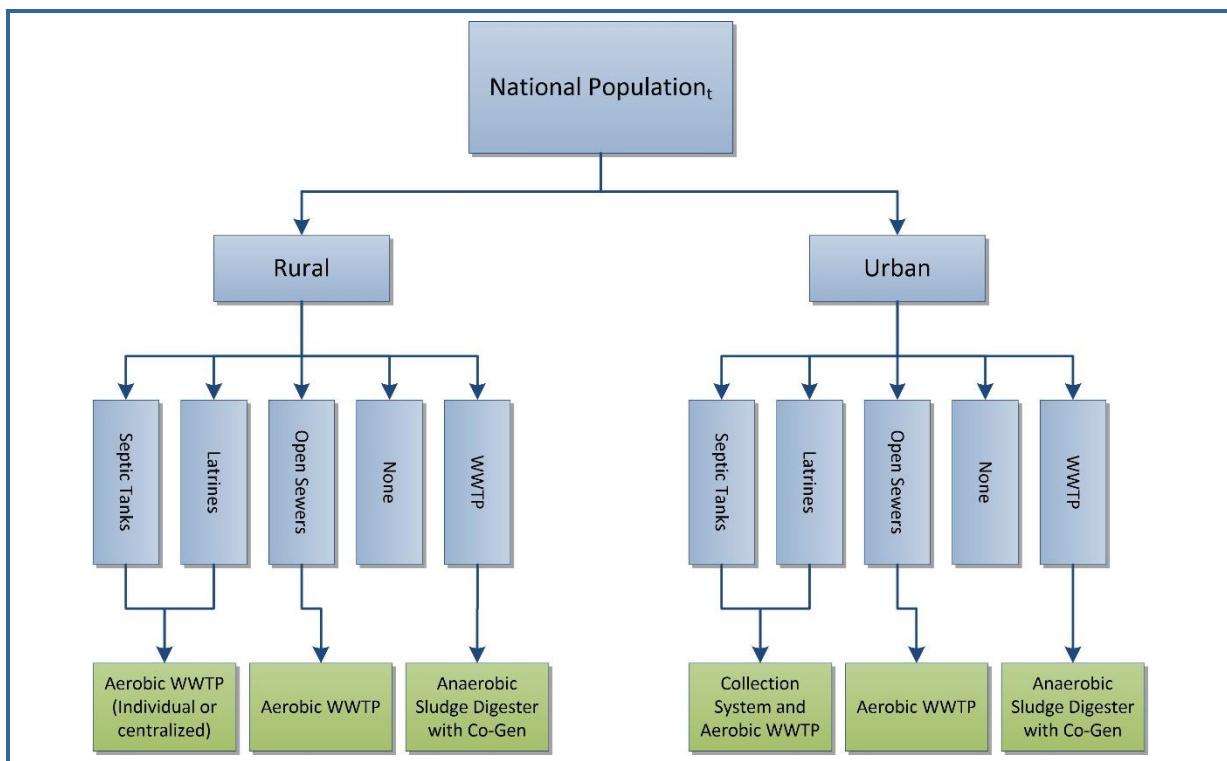
5.4.2.3 Sector-Level Trends and Considerations

The reader should bear in mind throughout the analysis that the wastewater sanitation technology is likely to be fixed by external factors, and improvements in technology will be driven by the population's desire/capacity for improved sanitation and hygiene, with any improvements to GHG emissions a secondary result of the change. Thus, although abatement measures are available, 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 by-product of a country's position on the sanitation ladder.

The MAC analysis is based on project costs developed for a set of model facilities based on the technical and economic parameters discussed above. 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 5-7 shows the organization of the domestic wastewater MAC model. The country-specific distributions are based on an analysis conducted by the EPA (2012).

Figure 5-7: Domestic Wastewater MAC Analysis Flow Chart





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 emission data obtained from the UNFCCC's GHG emission reporting database. Data were limited to 24 A1 countries accounting for 15% of emissions in 2010. For these 24 countries, we calculated a 5-year average share of CH₄ 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 emission projections are wholly attributable to domestic wastewater treatment systems to be consistent with EPA's (2012) projections methodology.

The analysis also leverages estimated changes in wastewater disposal activity along each wastewater treatment pathway discussed earlier in this section. These data were obtained from previous EPA analyses used to develop 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 were 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 reduce CH₄ emissions.

5.4.2.4 References

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5.4.3 Other Waste

This source category includes solid fuel transformation and waste incineration.

5.4.3.1 Other Energy Projections Methodology

This source category solely comprises countries that report data to the UNFCCC database. The EPA did not perform Tier 1 calculations for other energy sources. The EPA obtained historical values for 1990 through 2012 and held 2015 through 2050 values constant at 2012 levels for each country.

5.4.3.2 Other Energy Mitigation Methodology

The EPA has not estimated mitigation potential from other energy because of the lack of available data on mitigation options.