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Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990 - 2030

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About this Report

This report provides information on historical and projected estimates of emissions of non-CO_2 greenhouse gases from anthropogenic sources. It includes over 20 individual source categories from the energy, industrial processes, agriculture, and waste sectors. It covers 92 countries, historical information from 1990 to 2005 and business-as-usual projections from 2010 to 2030. This document is a revision of a draft document published to the EPA website in August 2011.

How to Obtain Copies

You may electronically download this document, and a shortened summary version of the report from the U.S. EPA's webpage at:
http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html.

How to Obtain the Data

You may electronically download the data compiled for this report in .xls format from the U.S. EPA's webpage at:
http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html.

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Expert Reviewed Document

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Acronyms

AI	Annex I
AE	anode effects
AR4	Fourth Assessment Report
BAU	business as usual
BOD	biological oxygen demand
CAGR	compound annual growth rate
CDM	Clean Development Mechanism
CEH	Chemical and Economics Handbook
CEIT	countries with economies in transition
CFC	chlorofluorocarbon
CF_4	perfluoromethane
C_2F_6	hexafluoroethane
C_3F_8	perfluoropropane
$c\text{-}C_4F_8$	perfluorocyclobutane
CH_4	methane
CIA	Central Intelligence Agency
CO_2	carbon dioxide
CRF	Common Reporting Format
CVD	chemical vapor deposition
CWPB	Center-Worked Prebake
DOC	degradable organic carbon
EDGAR	Emission Database for Global Atmospheric Research
EF	emission factor
EIA	Energy Information Administration
EMF-22	Energy Modeling Forum 22
EPA	U.S. Environmental Protection Agency
ESIA	European Semiconductor Industry Association
EU	European Union
F-GHG	fluorinated greenhouse gas
FAO	Food and Agriculture Organization of the United Nations
FOD	first order decay
FPD	flat panel display
FSU	Former Soviet Union
GDP	gross domestic product
Gg	gigagram
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HCFC-22	chlorodifluoromethane
HFC-23	trifluoromethane
HFC	hydrofluorocarbon
HFE	hydrofluoroethers

HSS	Horizontal Stud Soderberg
HTOC	Halon Technical Options Committee
IAI	International Aluminium Institute
IEA	International Energy Agency
IFA	International Fertilizer Industry Association
IFPRI	International Food Policy Research Institute
IMA	International Magnesium Association
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
JEITA	Japan Electronic and Information Technology Industries Association
JI	Joint Implementation
Kg	kilogram
KSIA	Korean Semiconductor Industry Association
MDI	metered dose inhalers
$MtCO_2e$	million metric tons of carbon dioxide equivalent
MSW	municipal solid waste
N	Nitrogen
N_2O	nitrous oxide
NAI	non-Annex I
NC	National Communication
NF_3	nitrogen trifluoride
NIK	not-in-kind
NIR	National Inventory Report
NO_x	Nitrogen oxides
ODP	ozone-depleting potential
ODS	ozone-depleting substance
OECD	The Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturers
OX	Oxidation
PFC	perfluorocarbons
PFPB	Point Feed Prebake
PRP	pasture, range, and paddock
PV	photovoltaic
SAR	Second Assessment Report
SF_6	sulfur hexafluoride
Si	Silicon
SIA	U.S Semiconductor Industry Association
SO_2	sulfur dioxide
SRES	Special Report on Emissions Scenarios
SWPB	Side-Worked Prebake
SWDS	solid waste disposal site
TAR	Third Assessment Report

TEAP	Technology and Economic Assessment Panel
TJ	terajoule
TMLA	total manufacture layer area
TSIA	Taiwan Semiconductor Industry Association
UNEP	United National Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VSS	Vertical Stud Soderberg
WEO	World Energy Outlook
WFW	World Fab Watch
WLICC	World LCD Industry Cooperation Committee
WSC	World Semiconductor Council
WWT	wastewater treatment
VAIP	Voluntary Aluminum Industrial Partnership

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1 Introduction and Overview

1.1 Introduction

This report provides historical and projected estimates of emissions of non-carbon dioxide (non-CO_2) greenhouse gases (GHGs) from anthropogenic sources. The report provides a consistent and comprehensive estimate of non-CO_2 greenhouse gases for 92 individual countries and eight regions. The analysis provides information that can be used to understand national contributions of GHG emissions, historical progress on reductions, and mitigation opportunities. Although this document is being published by the EPA, the U.S. projections are generated using the same methodologies used for all countries, and is based on IPCC Tier 1 calculations supplemented with country-reported inventory data where available. The dataset compiled for this report is available in spreadsheet (.xls) format on the U.S. EPA's webpage at: http://www.epa.gov/nonco2/econ-inv/international.html.

The gases included in this report are the direct non-CO_2 GHGs covered by the United Nations Framework Convention on Climate Change (UNFCCC): methane (CH_4), nitrous oxide (N_2O), and the Fluorinated Greenhouse Gases (F-GHG). The F-GHGs include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In addition, nitrogen fluoride (NF_3) is considered. Compounds covered by the Montreal Protocol are not included in this report, although many of them are also F-GHGs. Historical estimates are reported for 1990, 1995, 2000, and 2005 and projections of emissions are provided for 2010, 2015, 2020, 2025, and 2030. Projections reflect the currently achieved impact of sector-specific climate policy programs, agreements, and measures that are already in place, but exclude GHG reductions due to additional planned activities and economy-wide programs whose impacts on individual sectors are less certain.

To develop estimates included in this report, the U.S. Environmental Protection Agency (EPA) collected emission estimates from publicly available nationally-prepared GHG reports consistent with the *Revised 1996 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories* (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 *Revised 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories* (IPCC Guidelines) (IPCC, 2006). If national estimates were unavailable from nationally-prepared GHG reports, EPA estimated non-CO_2 GHG emissions in order to produce a complete global inventory. EPA's calculated emission estimates are 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.

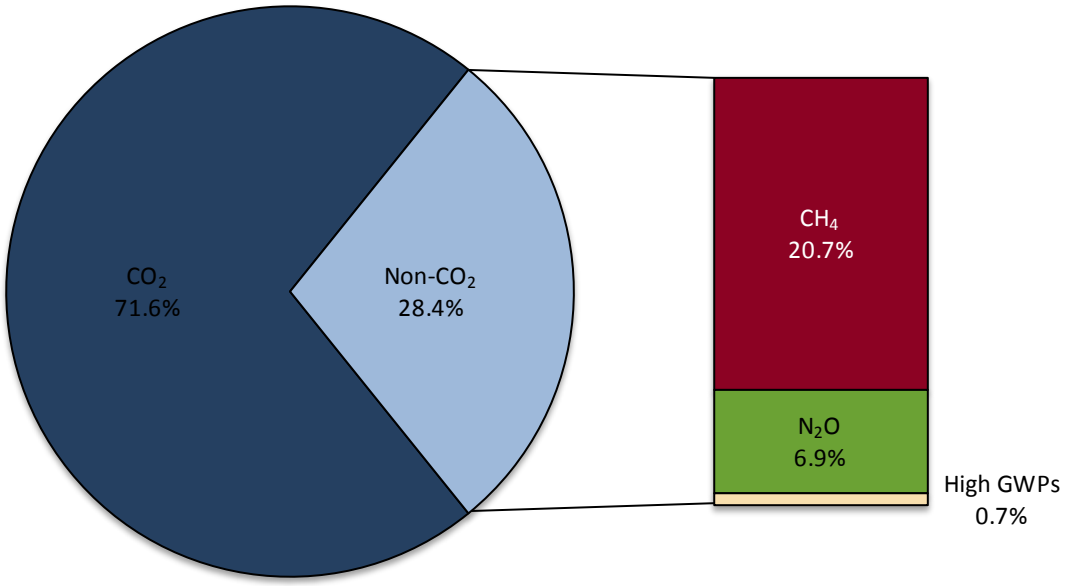
1.2 Overview of Non-CO_2 Greenhouse Gas Emissions

As shown in Exhibit 1-1, global emissions of CH_4, N_2O, and F-GHGs account for approximately 28 percent of global radiative forcing since the pre-industrial era of GHGs covered by the UNFCCC (IPCC, 2007). Emissions of non-CO_2 GHGs contribute significantly to radiative forcing[1] since they are more effective at trapping heat than CO_2. The IPCC uses the concept of the global warming potential (GWP) to compare the ability of different gases to trap heat in the atmosphere relative to

[1] Radiative forcing is the change in the balance between radiation coming into and going out of the atmosphere. Positive radiative forcing tends on average to warm the surface of the Earth, and negative forcing tends on average to cool the surface (IPCC, 2007).

CO_2. Emissions of non-CO_2 gases are converted to a CO_2-equivalent basis using the 100-year GWPs published in the IPCC's Second Assessment Report (SAR) (IPCC, 1996). Table 1-1 shows GWPs of select gases from IPCC's Second Assessment Report.[2] These GWPs, as well as GWPs for additional gases (see Table 4-1) were used in this report.

Exhibit 1-1: Contribution of Anthropogenic Greenhouse Gas Emissions to Global Radiative Forcing (W/m^2)



Source: IPCC, 2007: Table 2.1

Table 1-1: Global Warming Potentials

Gas	GWP[a]
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous Oxide (N_2O)	310
HFC-23	11,700
HFC-32	650
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900

[2] Although the GWPs have been updated by the IPCC in the Third Assessment Report (TAR) (IPCC, 2001) and again in the Fourth Assessment Report (AR4) (IPCC, 2007), estimates of emissions in this report continue to use the GWPs from the Second Assessment Report (SAR) (IPCC, 1996), in order to be consistent with international reporting standards under the UNFCCC. However, some of the F-GHGs estimated in this report do not have GWPs in the SAR. In these cases, this report uses the TAR GWPs or other published data(see Table 4-1 for additional gases).

Gas	GWP[a]
HFC-236fa	6,300
HFC-4310mee	1,300
CF_4	6,500
C_2F_6	9,200
C_4F_{10}	7,000
C_6F_{14}	7,400
SF_6	23,900

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

EPA estimates that global non-CO_2 GHG emissions in 2005 were about 11,000 million metric tons of carbon dioxide equivalents ($MtCO_2e$[3]). When this non-CO_2 emissions estimate is added to a global CO_2 emissions estimate for 2005 of approximately 32,000 $MtCO_2$ (WRI, 2010), anthropogenic non-CO_2 emissions represent 25 percent of the global GHG emissions emitted annually on a CO_2 equivalent basis in 2005.

1.3 Emission Sources

This report focuses exclusively on anthropogenic sources of non-CO_2 GHGs. Table 1-2 lists the source categories discussed in this report. All anthropogenic sources of CH_4 and N_2O are included (with a few exceptions noted in Section 1.6). The major sources are considered individually and emissions from minor sources are combined under "Other" categories, listed in Table 1-2. The F-GHG sources include substitutes for ozone-depleting substances (ODS) and industrial sources of HFCs, PFCs, and SF_6.

[3] One $MtCO_2$ is equivalent to one megatonne or teragram of CO_2.

Table 1-2: 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_2O
Biomass Combustion	CH_4, N_2O
Other Energy Sources	
Waste Combustion	CH_4, N_2O
Fugitives from Solid Fuels	N_2O
Fugitives from Natural Gas and Oil Systems	N_2O
Industrial Processes	
Adipic Acid and Nitric Acid Production	N_2O
Use of Substitutes for Ozone Depleting Substances	HFCs
HCFC-22 Production	HFCs
Electric Power Systems	SF_6
Primary Aluminum Production	PFCs
Magnesium Manufacturing	SF_6
Semiconductor Manufacturing	HFCs, PFCs, SF_6, NF_3
Flat Panel Display Manufacturing	PFCs, SF_6, NF_3
Photovoltaic Manufacturing	PFCs, NF_3
Other Industrial Processes Sources	
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
Agriculture	
Agricultural Soils	N_2O
Enteric Fermentation	CH_4
Rice Cultivation	CH_4
Manure Management	CH_4, N_2O
Other Agriculture Sources	
Agricultural Soils	CH_4
Field Burning of Agricultural Residues	CH_4, N_2O
Prescribed Burning of Savannas	CH_4, N_2O
Open Burning from Forest Clearing	CH_4
Waste	
Landfilling of Solid Waste	CH_4
Wastewater	CH_4
Human Sewage - Domestic Wastewater	N_2O
Other Waste Sources	
Miscellaneous Waste Handling Processes	CH_4, N_2O

Sources of Non-CO_2 Greenhouse Gas Emissions Not Included in This Estimate

Due to methodological limitations, a few anthropogenic sources have not been fully included in this analysis. These include CH_4 from hydroelectric reservoirs and abandoned coal mines, N_2O from industrial wastewater, and F-GHG emissions from the manufacture of electrical equipment. Information on these sources is partially included because historical and projection data taken from country-reported inventories and national communication may include emissions data from one or more of these sources. EPA did not calculate tier 1 estimates for these sources where it was missing, nor subtract out values from country reports where it was included. For this reason, the sources covered by the wastewater, electric power systems, and coal mine estimates may be slightly different between countries with country-reported emissions versus tier 1 estimates. In addition, natural sources of non-CO_2 emissions are not included in this report because policies focus on anthropogenic emissions sources as opposed to natural sources which include long-term background levels of GHG emissions.[4]

1.4 Region Groupings

Countries in this report have been grouped for the purpose of charts and analysis. These regions are defined based on a combination of geographic regions and OECD membership status:

- OECD
- non-OECD Asia,
- non-OECD Europe and Eurasia,
- Africa,
- Central and South America, and
- the Middle East.

OECD membership status is used as of November, 2010. At that time, Chile, Israel, and Slovenia had recently joined the OECD. Chile and Israel are included in the OECD as opposed to Central and South America and Middle East regions. Likewise, Slovenia is included in the OECD as opposed to the non-OECD Europe and Eurasia region.

[4] For more information see EPA Report 430-R-10-001 "Methane and Nitrous Oxide Emissions from Natural Sources."

Exhibit 1-2: Regional Groupings

OECD

Australia [A]
Austria [A, E]
Belgium [A, E]
Canada [A]
Chile
Czech Republic [A, E]
Denmark [A, E]
Finland [A, E]
France [A, E]
Germany [A, E]
Greece [A, E]
Hungary [A, E,]
Iceland [A]
Ireland [A, E]
Israel
Italy [A, E]
Japan [A]
Luxembourg [A, E]
Mexico
Netherlands [A, E]
New Zealand [A]
Norway [A]
Poland [A, E]
Portugal [A, E]
Slovakia[A, E]
Slovenia [A, E]
South Korea
Spain [A, E]
Sweden [A, E]
Switzerland [A]
Turkey [A]
United Kingdom (UK) [A, E]
United States (U.S.) [A]

Non-OECD Europe & Eurasia

Albania
Armenia
Azerbaijan
Belarus [A]
Bulgaria [A, E]
Croatia [A]
Estonia [A, E]
Georgia
Kazakhstan
Kyrgyzstan
Latvia [A, E]
Lithuania [A, E]
Macedonia
Moldova
Monaco [A]
Romania [A, E]
Russia [A]
Tajikistan
Turkmenistan
Ukraine [A]
Uzbekistan
"Rest of Non-OECD Europe & Eurasia" [1, 2]

Africa

Algeria [O]
Congo (Kinshasa)
Egypt
Ethiopia
Nigeria [O]
Senegal
South Africa
Uganda
"Rest of Africa" [1, 2]

Central and South America

Argentina
Bolivia
Brazil
Colombia
Ecuador [O]
Peru
Uruguay
Venezuela [O]
"Rest of Central and South America"[1, 2]

Non-OECD Asia

Bangladesh
Burma
Cambodia
China
India
Indonesia
Laos
Mongolia
Nepal
North Korea
Pakistan
Philippines
Singapore
Thailand
Vietnam
"Rest of Non-OECD Asia" [1, 2]

Middle East

Iran [O]
Iraq [O]
Jordan
Kuwait [O]
Saudi Arabia [O]
United Arab Emirates [O]
"Rest of Middle East" [1, 2]

Codes:
A – Annex I Countries
E – European Union Countries
O – OPEC Countries

Notes:

1. The complete list of countries included in the "Rest of" groupings can be found in Appendix J.
2. In this report, when emissions totals are presented for a region, the regional sum includes the estimates for all of the individually reported countries *and* the aggregated value for the "Rest of" countries. For example, the emissions total for the "Middle East" found in the graphs and Appendices A through D, includes the sum of Iran, Iraq, Israel, Jordan, Kuwait, Saudi Arabia, the United Arab Emirates *and* the smaller emitters already aggregated under "Rest of Middle East".

These regional country groupings are further defined in Exhibit 1-2 and Appendix J.

1.5 Approach

In this report, EPA presents historical emission estimates for individual countries for 1990, 1995, 2000, and 2005. Projected emissions, assuming no additional reduction measures, were estimated from 2010 to 2030, also at five-year intervals. In addition to the individual country data, EPA presents overall trends by region, gas, and source category and explanations for why these trends are projected.

The general approach for developing the estimates used a combination of country-prepared, publicly-available reports of emissions and calculations based on activity data and default emission factors. The base year for projections was 2005. Estimates from 1990 to 2005 are the historical period and estimates of actual emissions. Estimates from 2010 to 2030 are projections. Emissions projections required a range of assumptions about economic activity, technology development, and emissions reductions, and other factors.

The projections represent a business-as-usual (BAU) scenario where currently achieved reductions are incorporated and future mitigation actions are included only if either a well-established program or an international sector agreement is in place. Estimates in this report are presented at the source category level; therefore, only policies and programs that affect source level emissions directly were reflected in the BAU projections. For example, the reductions attributable to the EU landfill directive regulations, U.S. sector level voluntary programs, and international sector agreements such as the World Semiconductor Council agreement were reflected in BAU projections presented here. The reductions associated with Kyoto commitments and Copenhagen reduction pledges were not reflected in projections by GHG or source category because these are country level goals that are difficult to disaggregate to the required degree.

Data Sources

The three primary types of data used in this report are country-prepared emissions reports, activity data, and default emission factors. Country-reported data include Annex I inventory submissions to the UNFCCC Secretariat which consist of a National Inventory Report (NIR) and Common Reporting Format (CRF), National Communications to the UNFCCC, and/or other country-prepared reports. The preferred source for historical data was the UNFCCC flexible query system (UNFCCC, 2012) since this database provides updated GHG emission estimates for most Annex I Parties and to a lesser extent the latest GHG emission estimates for non-Annex I Parties. [5] National Communications were the preferred source for projections and non-Annex I historical emission estimates. The Fifth National Communications were available for most Annex I Parties. For non-Annex I countries, a majority have submitted their First National Communications, 29 had Second National Communications, and one country had both a Third and Fourth National Communications. The estimates in the UNFCCC inventory submissions and National Communications for each reporting Party are comparable because they rely on the IPCC methodologies and are reported for IPCC-designated source categories which generally follow the categories shown in Table 1-2.

For most Annex I Parties, a full historical time series of emissions inventories was available from national inventory reports. In some cases, this report also used emissions projections provided by

5 Annex I Parties include the industrialized countries that were members of the OECD in 1992, plus countries with economies in transition (the CEIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States. Annex I countries are noted in Exhibit 1-2.

Annex I Parties in their National Communications. However, in many cases emissions projections from National Communications use aggregated or differing categories which make them difficult to use for disaggregated source-specific projections. Non-Annex I Parties do not file yearly national inventory reports, but they do produce National Communications. Those National Communications include historical inventories and projections in some cases. However, most non-Annex I countries provided their most recent National Communication prior to 2005, meaning some historical period emissions data use projections and calculations.

In addition to country-reported data, this report utilized international activity data sources and default emission factors. For example, activity data sources included coal and oil production compiled by the International Energy Agency, primary aluminum production compiled by the U.S. Geological Survey, fertilizer usage and crop production compiled by the Food and Agriculture Organization, and population and GDP data and projections. Information on data sources used for each emissions source can be found in Section 7. Activity data were used with default emission factors provided in IPCC emissions calculation guidelines to estimate emissions. In some cases, projections of activity data were available. In other cases, growth rates were extrapolated from historical data.

Emissions Calculations

If nationally developed emission estimates were unavailable or if the data were insufficient, EPA estimated historical emissions and projections using the default methodologies presented in the IPCC Guidelines (available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html) and the IPCC Good Practice Guidance (available at: http://www.ipcc-nggip.iges.or.jp/public/gp/english/). EPA used IPCC Tier 1 methodologies and available country or region-specific activity data to estimate emissions. Some of these calculations relied on population estimates provided by the U.S. Census International Database and GDP estimates from the U.S. Department of Agriculture.

IPCC guidelines provide three tiers of calculation methods which provide different levels of accuracy based on available data. Tier 1 methodologies are the simplest methods, requiring the least data but have the greatest uncertainty. Tier 1 estimates usually involve activity data statistics multiplied by a default emission factor.

Many sources and countries had some years for which country-reported data is available, and others for which calculations were necessary. In most of these cases, growth rates were calculated using Tier 1 methodology (historical or projected activity data and Tier 1 emission factors); these rates were then applied to country-reported estimates to project emissions. One advantage of this approach is that it avoids reporting discontinuities or changes in emissions because of changes in methodology. It also implicitly uses emission factor information from country-reported emissions data, which may use more accurate methodologies than the Tier 1 calculations. The disadvantage, however, is that some emission estimates are a hybrid of country-reported and calculated emissions.

A detailed description of the methodology used for each country and source category can be found in Section 7 and Appendix G.

1.6 Limitations

Although careful and consistent methods have been used to produce the emissions estimates in this report, they have limitations. First, some data were not incorporated into the estimates due to methodological and time limitations. In addition, the methods entail significant uncertainty. Third,

policies and economic development are likely to diverge from the business-as-usual assumptions that were used to construct the projections.

This report primarily uses recent information available as of April 2010 and reported UNFCCC data available as of March 2012. More recent estimates of emissions and activity data are available for some countries and sectors, but were not incorporated due to time limitations. These more recent information include GHG emission estimates from Annex I national inventory report submissions for 2010, several non-Annex I National Communications, emission estimates from biomass burning from EDGAR (the Emission Database for Global Atmospheric Research), energy and fuel use data from IEA (Energy Balances of OECD and Non-OECD Countries), projections of energy and fuel use from IEA's World Energy Outlook and EIA's International Energy Outlook, population estimates from the U.S. Census, and GDP estimates from USDA. In addition, some data sources were not used because of methodological limitations or because time was not available to develop calculations to utilize those sources. For example, National Communications often present aggregated emissions projections, which are difficult to use to project emissions by source.

The projections are sensitive to changes in key assumptions regarding technological changes and production/consumption patterns. For example, the emission rates of new equipment using ODS substitutes are likely to be much lower than the emission rates of older equipment. This newer equipment is only now being phased in, and the long-term emission characteristics are not yet well known. In the agriculture sector, the effect of changing consumer preferences on product demand, such as increased beef consumption, is difficult to predict and creates large uncertainties in the projected emissions from many of the agricultural sources. In general, Tier 1 calculations include significant uncertainty because they do not utilize detailed information but instead use average emission rates for a category.

While efforts have been made to provide projected emissions on a consistent basis, the distinction between currently achieved GHG reductions from climate mitigation measures in place and those from additionally planned activities is not always clearly defined in the reported data. The inclusion of incidental GHG reductions in projected emissions as a result of climate related actions or government polices still in development is a possibility in some isolated cases. However, due to the consistent approaches established for reporting projected data and policies and measures in the National Communications, the information developed from these sources is generally considered comparable.

The projections in this report used BAU assumptions. However, many countries have already committed to actions to reduce their emissions below the BAU level. The extent to which actions will affect CO_2 and non-CO_2 emissions is uncertain. In addition, the projections used constant emission factors, which do not account for future changes in emission rates due to technological development (such as low-emissions technologies).

For all these reasons, uncertainty in the emissions projections is significant. Care should be used in examining emissions projections for a single country or source, especially in examining small changes for which uncertainty can alter conclusions. Nonetheless, EPA believes that these estimates and projections represent a reasonable and detailed approximation with the data and resources available.

1.7 Organization of this Report

The remainder of this report expands upon the results of this analysis in six main sections. Section 2 presents a summary of global emissions and briefly discusses global trends. Sections 3 through 6 present source descriptions and emission estimates for CH_4, N_2O, and F-GHG emissions for each of the following sectors: energy, industrial processes, agriculture, and waste. Within each of these chapters, the discussion is divided into key sources that contribute to non-CO_2 GHG emissions. These source category discussions present an overview of global emissions for that category and regional trends for 1990 to 2030. Section 7 presents the methodology used to collect the most recent emissions inventory and projection data, and the data sources and methods used to adjust the available data for each country. The appendices include detailed emission estimates by country, sector and source; a description of methodologies applied for each country and source; data sources used; future mitigation measures included for some sources; regional definitions; and a description of EPA's Vintaging Model Framework used to estimate emissions of ODS substitutes in the U.S.

2 Summary Results

2.1 Summary Estimates

Between 1990 and 2005, global non-CO_2 emissions grew by 10 percent from about 9,800 to 10,800 $MtCO_2e$ and are expected to grow approximately 43 percent from 2005 to 2030. This projection represents a BAU scenario in which currently achieved reductions are incorporated but future mitigation actions are included only if either a regulation, well-established program, or an international sector agreement is in place.[1] Historical emissions of CH_4 have increased 9 percent (from about 6,300 to 6,800 $MtCO_2e$), N_2O emissions increased 4 percent (from about 3,200 to 3,400 $MtCO_2e$), and F-GHG emissions increased 128 percent (from about 250 to 600 $MtCO_2e$) from 1990 to 2005. Emissions of F-GHGs are projected to increase 336 percent from 2005 to 2030, much faster than CH_4 (26 percent) and N_2O (26 percent).

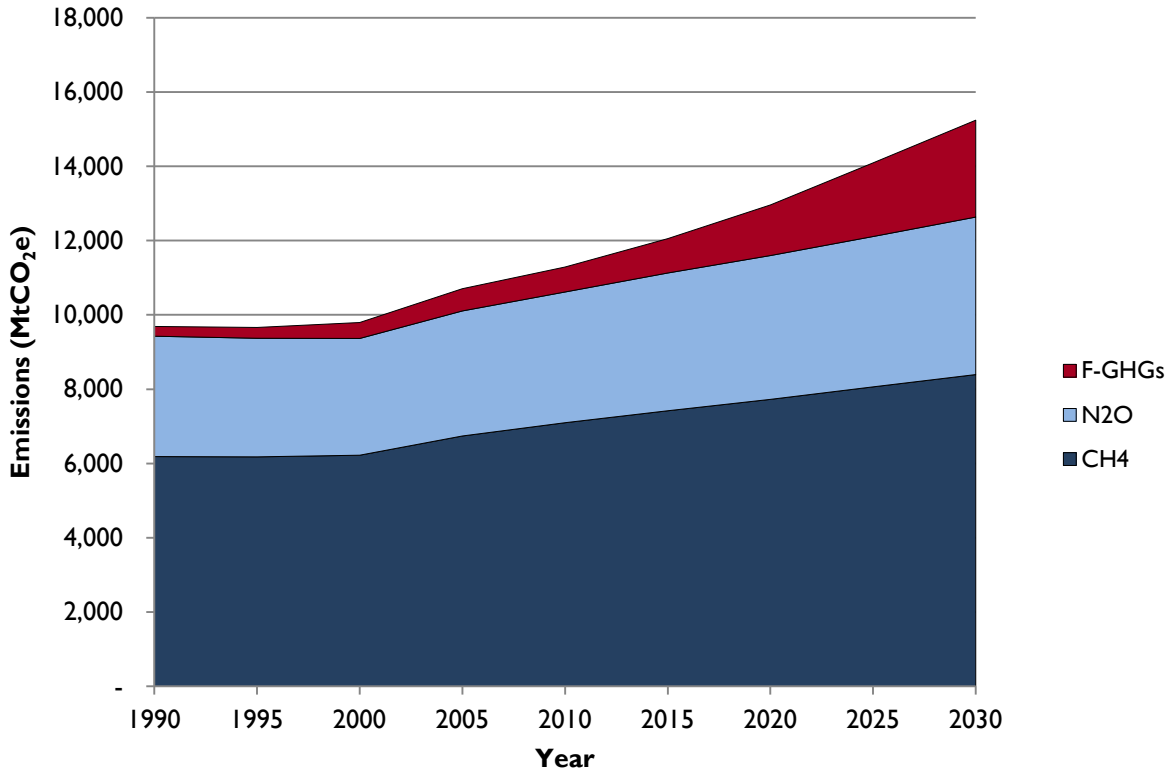
Historical emission trends for CH_4 and N_2O are the cumulative effect of several drivers. Although basic activities (waste generation and landfilling, energy production and consumption, etc.) have predominantly increased, several factors have mitigated emission growth. First, recovery and use of CH_4 has reduced these emissions in many countries. Second, sectoral level restructuring has decreased emissions. Finally, economic restructuring in several countries, such as Russia and Germany, caused a decrease in emissions in the 1990s. Since 2000, emissions have increased due to a number of factors, driven largely by 1) economic and sectoral growth in recently restructured countries and sectors, and 2) only partial mitigation coverage in the BAU projections (as described above). F-GHG emissions, although relatively small in 1990, have increased substantially as HFCs have been deployed as substitutes for the ozone-depleting substances (ODS) that are being phased out globally under the Montreal Protocol. This historical deployment of HFCs has taken place primarily in developed countries, where hydrofluorocarbon (HCFC) phaseout regulations have been promulgated, although emissions are also now present in developing countries where HFCs are being used as direct replacements for the globally-phased out chlorofluorocarbons (CFCs) in some technologies (e.g., air conditioning for passenger cars).

Projections of future growth in emissions of non-CO_2 gases are driven by several factors. Countries with fast-growing economies and populations are expected to contribute more to the global CH_4 and N_2O totals as their economies grow, energy consumption increases, and waste generation rates increase. Countries with more steady-state economies, and small or even declining population growth rates, are likely to experience minimal growth in CH_4 and N_2O emissions. The large increase in F-GHG emissions stems predominately from the increase in use of HFCs as substitutes for ozone depleting substances. While this trend has largely been observed only for OECD countries to 2005, throughout the projection period all regions are projected to have increases in HFC emissions, as more countries transition away from ODSs amidst strong global growth in demand expected for refrigeration and air conditioning and other technologies that utilize HFCs in lieu of ODSs. While emissions of HFCs used as substitutes for ODSs are increasing, the ODSs which HFCs replace are

[1] Estimates in this report are presented at the source category level, therefore, only policies and programs that affect source level emissions directly are reflected in the BAU projections. For example, the reductions attributable to the EU landfill directive regulations, U.S. sector level voluntary programs, and international sector agreements such as the World Semiconductor Council agreement are reflected in BAU projections presented here. The reductions associated with Kyoto commitments and Copenhagen targets are not taken into account because these are country level goals that are difficult to disaggregate to the source category level.

also greenhouse gases, in many cases more potent than the substitutes. Thus, although emissions of HFCs used as substitutes of ODSs are increasing, the radiative forcing from the CFCs and HCFCs they replace would have been much higher had the phaseout of ODSs not taken place.[2]

Exhibit 2-1: Global Non-CO_2 Emissions, by Gas ($MtCO_2e$)



2.2 Trends by Region

Exhibit 2-2 shows the regional contribution of emissions from 1990 to 2030. Between 1990 and 2005, emissions grew from Africa, Central and South America, the Middle East, and non-OECD Asia, while falling from the OECD and non-OECD Europe and Eurasia regions. By 2030, BAU emissions of non-CO_2 GHGs are projected to increase in every region compared to 2005 emissions. Emissions are projected to grow the fastest in non-OECD Asia, the Middle East, and the OECD. Table 2-1 displays decadal growth rates by region from 1990 to 2030.

[2] For an estimate of the climate benefits of phasing out ODSs, see Velders et al. (2007).

Exhibit 2-2: Total Global Non-CO_2 Emissions, by Country Grouping ($MtCO_2e$)

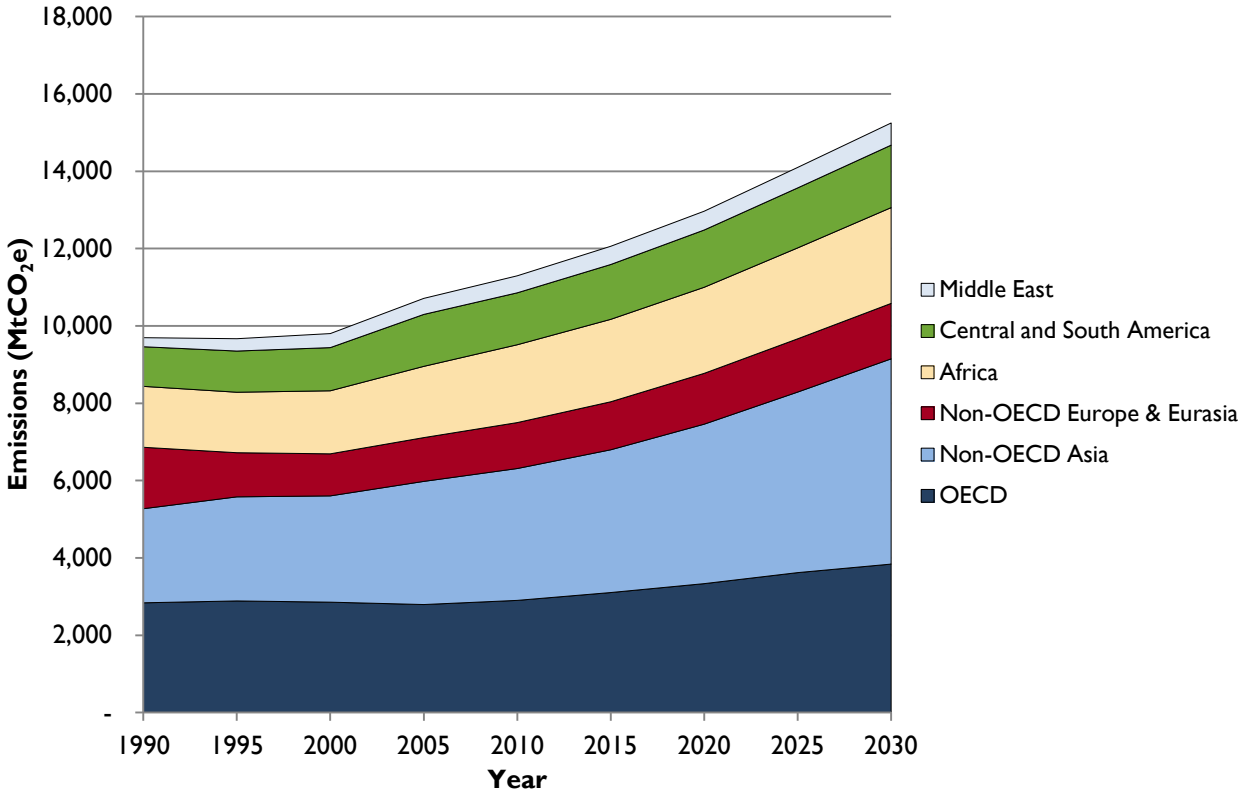


Table 2-1: Percent Change in Total Global Non-CO_2 Emissions, by Decade and Region

Region	1990-2000	2000-2010	2010-2020	2020-2030	1990-2030
OECD	0.6%	1.6%	14.9%	15.2%	35.3%
Non-OECD Asia	13.0%	24.1%	20.9%	28.7%	118.1%
Non-OECD Europe & Eurasia	-31.6%	9.2%	10.6%	9.1%	-9.7%
Africa	3.5%	23.5%	10.6%	11.3%	57.2%
Central and South America	8.9%	20.3%	10.3%	9.1%	57.7%
Middle East	47.4%	16.0%	20.6%	18.1%	143.4%
Total	1.3%	15.1%	15.2%	17.6%	58.0%

Non-CO_2 emissions from the OECD decreased by 2 percent from 1990 to 2005 (to about 2,800 $MtCO_2e$), while GDP grew by 44 percent.[3] Several initiatives took place during this period which had the effect of reducing emissions. Some of the most significant were increasing control of emissions from nitric acid, adipic acid, and HCFC-22 manufacturing facilities, tailpipe emissions from vehicles, and capture and combustion of landfill gas. Coal production declined significantly in the EU, which decreased emissions from coal mining. Emissions from OECD countries are projected to increase 37 percent (from 2,800 to 3,800 $MtCO_2e$) from 2005 to 2030. This scenario does not take into account economy-wide programs to control GHG emissions or country

[3] EIA, 2009. GDP is expressed in constant 2005 dollars, at market exchange rates. Table A4 from the International Energy Outlook 2009.

emissions reduction pledges. While some emissions reduction activities that have been successful in the OECD in the past will likely continue to be significant, large additional reductions in those areas are less likely since many-cost effective options have already been implemented.

The non-OECD Europe and Eurasia region includes many countries from the former Soviet Union which underwent significant economic changes since 1990. Non-CO_2 emissions from this region dropped 29 percent between 1990 and 1995, and stayed at approximately this level through 2005. The emissions decline can be attributed to economic contraction, with GDP in 2005 2 percent lower than 1990, as well as changes in industry structure that accompanied the change to market economies. From 2005 to 2030, emissions from this region are projected to grow 27 percent, which would result in emission totals nearly reaching 1990 levels.

Non-OECD Asia has grown quickly from 1990 to 2005, both in terms of economy and emissions. Over this period, non-CO_2 emissions grew 31 percent (from about 2,400 to 3,200 $MtCO_2e$), while GDP grew by 178 percent, nearly tripling the previous level. International offset projects have been concentrated in this region, and especially in the HCFC-22 manufacturing sector, but emissions in this sector have continued to increase. Because national inventory reports are not available from the largest emitters in this region, historical emissions have been estimated using activity data and IPCC default emission factors. Recent initiatives to close small mines in China may be reducing CH_4 emissions from the coal mining sector. From 2005 to 2030, non-CO_2 emissions from non-OECD Asia are projected to grow by 67 percent, with GDP more than quadrupling (increasing by 327 percent). Two factors are expected to cause ODS substitute emissions to grow significantly: the phase-out of ODSs and the increasing use of air conditioning and refrigeration as economies grow. Emissions from many industries are expected to grow in parallel with economic expansion.

Non-CO_2 emissions from Africa grew 17 percent between 1990 and 2005. GDP in Africa grew 57 percent over the same period. The pattern of emissions is quite different in Africa than other regions. Sources with significant emissions and growth over this period include savanna burning (included in other agricultural sources), biomass burning, natural gas and oil, stationary and mobile combustion, landfills and wastewater. Emissions from Africa are projected to increase 34 percent from 2005 to 2030, while GDP is expected to triple over this time. As African economies develop, technologies used are likely to change substantially, impacting non-CO_2 emission trajectories. Such changes aren't generally accounted for in the BAU projections.

Between 1990 and 2005, emissions from Central and South America[4] grew 31 percent, while GDP grew by 55 percent. About 82 percent of non-CO_2 emissions in Central and South America are attributed to the Agriculture sector in 2005, a much higher proportion than other regions. From 2005 to 2030, emissions from the region are projected to increase 20 percent, the smallest percentage increase of all regions. GDP is expected to grow 157 percent over the projection period, slower than any of the other non-OECD regions.

Emissions from the Middle East[5] region grew 55 percent from 1990 to 2005. While, this rate of growth is the near the highest of any region, emissions from the Middle East comprise only 5 percent of the world total in 2005. Over half of non-CO_2 emissions from the Middle East (on a CO_2 equivalent basis) are CH_4 emissions from the natural gas and oil sector; thus the emissions trend for

[4] The Central and South America region excludes Chile, which recently joined the OECD and is included in that region.

[5] The Middle East region excludes Israel, which recently joined the OECD and is included in that region.

the region is highly correlated with trends in oil and gas production. From 2005 to 2030, emissions from the region are projected to grow by 57 percent.

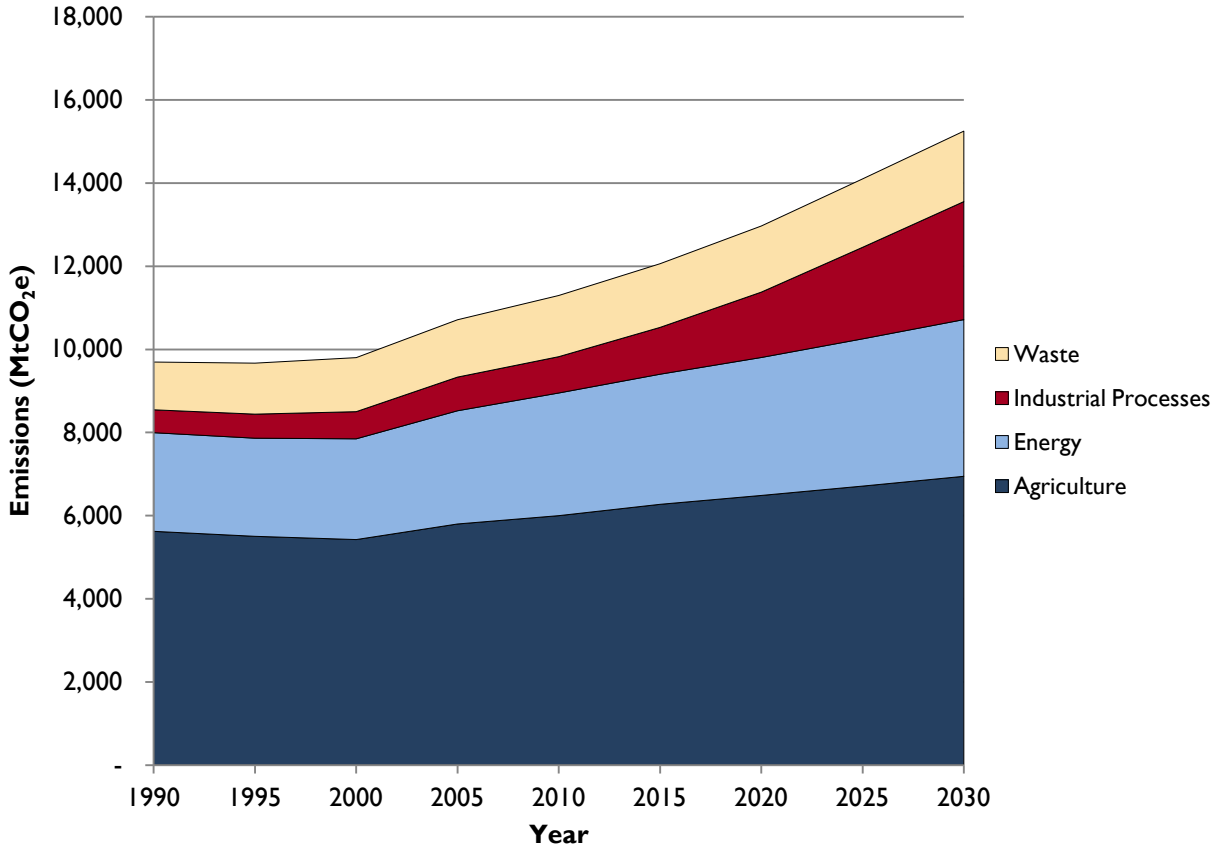
2.3 Trends by Gas, Sector, and Source Category

Emissions sources are grouped into four economic sectors: energy, industrial processes, agriculture and waste. While CO_2 emissions are concentrated in the energy sector, agriculture accounts for the largest share of non-CO_2 emissions (54 percent of emissions in 2005). The energy, waste, and industrial processes sectors account respectively for 26 percent, 8 percent, and 13 percent of emissions in 2005. However, emissions from industrial processes are growing at a faster rate than emissions from the other sectors.

The agricultural sector is the largest source of non-CO_2 emissions, as illustrated in Exhibit 2-3. Emissions from agricultural sources accounted for 58 percent of global non-CO_2 emissions in 1990, and is expected to remain the largest contributor of emissions in 2030. However, by 2030 the sector's share is expected to decrease to 45 percent of global non-CO_2 emissions. Agricultural sector emissions have increased 3 percent between 1990 and 2005 (from about 5,600 to 5,800 $MtCO_2e$). Emissions from the agricultural sector are projected to further increase by 20 percent by 2030 (to about 6,900 $MtCO_2e$). Emissions from all regions are expected to grow between 2005 and 2030. The largest emissions sources within the agricultural sector are N_2O emissions from agricultural soils and CH_4 from enteric fermentation, which account for 32 and 33 percent of non-CO_2 emissions from agriculture in 2005, respectively. Agricultural soil emissions are projected to increase 35 percent between 2005 and 2030, representing the largest increase among agricultural sources during this timeframe. Exhibit 2-4 shows trends for the largest sources of non-CO_2 emissions.

Energy sector emissions are the second largest source of non-CO_2 emissions, accounting for approximately 25 percent of non-CO_2 emissions in the 1990 to 2005 period. Emissions from the energy sector increased 14 percent between 1990 and 2005 (from about 2,500 to 2,800 $MtCO_2e$), driven by a 21 percent increase in emissions from natural gas and oil systems. In 2005, fugitive emissions from natural gas and oil systems represented the largest source of non-CO_2 GHG emissions from the energy sector, accounting for 55 percent of energy-related emissions. The next largest source in this sector is emissions from coal mining activities, accounting for 19 percent of energy related emissions in that year. From 2005 to 2030, energy sector emissions are projected to increase 42 percent (to about 4,000 $MtCO_2e$), with emissions from stationary and mobile combustion and coal mining activities increasing by 59 and 50 percent, respectively.

Exhibit 2-3: Total Global Non-CO_2 Emissions, by Sector ($MtCO_2e$)



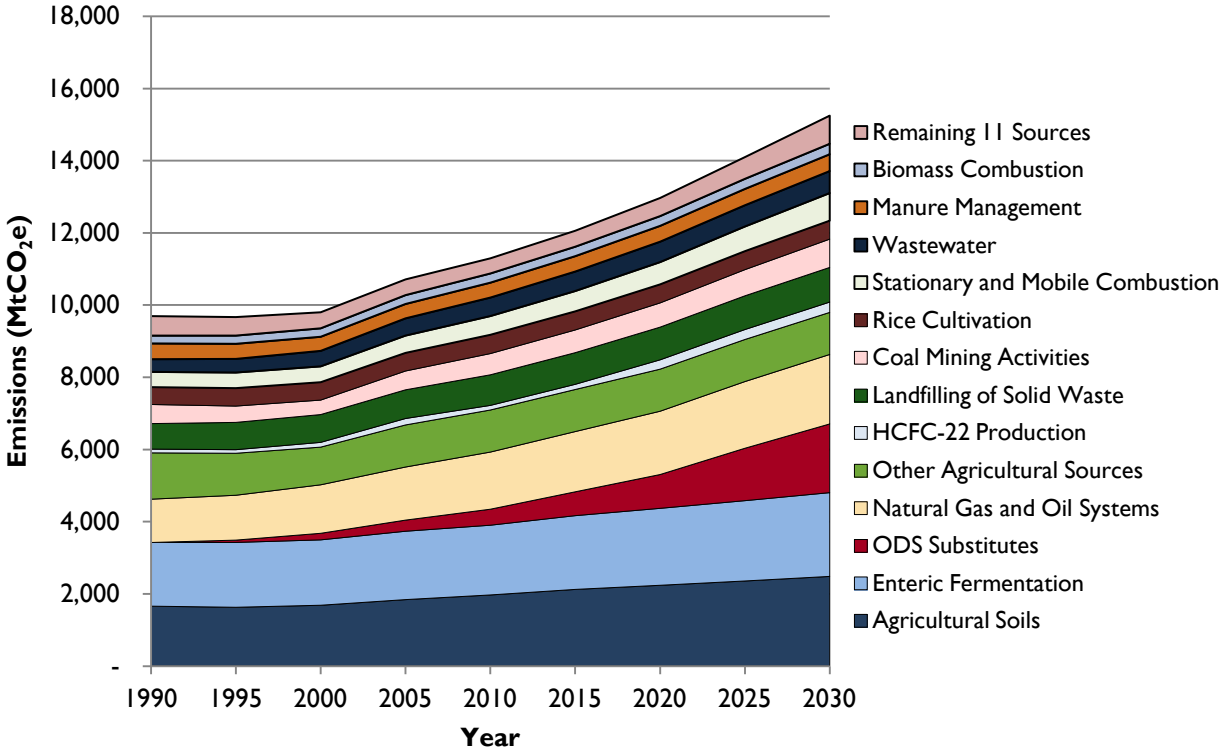
The industrial processes sector was the smallest contributor to global emissions of non-CO_2 greenhouse gases in 2005, accounting for only 8 percent of total emissions. As the fastest growing of all sectors, emissions from industrial processes are projected to increase to 18 percent of non-CO_2 greenhouse gases in 2030, surpassing emissions from the waste sector. The industrial processes sector includes all emissions of F-GHGs as well as N_2O emissions from nitric and adipic acid production and other industrial process sources. In 1990, nitric and adipic acid production accounted for 36 percent of non-CO_2 emissions from the sector. Between 1990 and 2005, emissions from nitric and adipic acid declined significantly due to the installation of abatement equipment. However, emissions from production of HCFC-22 and ODS substitutes increased over the same time period. Emissions from the industrial processes sector as a whole have increased 47 percent between 1990 and 2005 (from about 550 to 800 $MtCO_2e$) and are projected to grow even faster, nearly quadrupling between 2005 and 2030 (from about 800 to 2,800 $MtCO_2e$). This sectoral growth is driven by growth in emissions from ODS substitutes over this period, due to the phase out of ODSs under the Montreal Protocol and strong predicted growth in traditional ODS applications (e.g., refrigeration and air conditioning). As ODSs are phased out, other gases, including HFCs and to a limited extent PFCs, are substituted. The rate of growth is uncertain, however, because the choice of chemicals and potential new technologies or operating procedures could eliminate or diminish the need for these gases. However, under the BAU scenario without further controls, it is assumed that most users will switch to HFCs.

The waste sector was the third largest contributor to global emissions of non-CO_2 greenhouse gases in 2005, accounting for 13 percent of total emissions. In the waste sector, the two largest sources of

non-CO_2 emissions are landfilling of solid waste and wastewater, together contributing 92 to 93 percent of emissions throughout the 1990 to 2030 period. CH_4 from landfills accounts for an average of 58 percent of waste emissions across the same timeframe. Increases in waste generation and population drive global waste emissions upward but increases in waste-related regulations and gas recovery and use are expected to temper this increase. Emissions from wastewater are projected to grow more quickly than those from landfills, and are projected to account for 36 percent of waste emissions by 2030. Projected wastewater emissions are driven by population growth and the underlying assumption that growing populations in the developing world are largely served by latrines and open sewers, rather than advanced wastewater treatment systems.

Exhibit 2-4 displays the breakdown of global non-CO_2 emissions by source. Thirteen sources are expected to contribute almost all (95 percent) of non-CO_2 emissions in 2030. Four of these sources—agricultural soils, enteric fermentation, ODS substitutes, and natural gas and oil systems—are projected to contribute over half (57 percent) of the global total in 2030.

Exhibit 2-4: Global Non-CO_2 Emissions, by Source ($MtCO_2e$)



2.4 Other Global Datasets

Although non-CO_2 global emissions data are not as prevalent as CO_2 data, other datasets exist and EPA has included information on those datasets for comparison. It should be noted that in some cases, those datasets rely partly on either segments or earlier versions of the dataset presented in this report. Additionally, the dataset presented in this report includes data on biomass burning taken from the Emission Database for Global Atmospheric Research (EDGAR).

Table 2-2 and Exhibit 2-5 present global historical and projected emissions of CH_4, N_2O, and F-GHGs for 2000, 2010, 2020, and 2030 from the following sources:

- Energy Management Forum 22 (EMF-22) Analysis (EMF-22, 2009).[6]
- CCSP Synthesis and Assessment Product 2.1 - Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (CCSP, 2007).[7]
- Emission Database for Global Atmospheric Research (EDGAR) 4.1 (EC-JRC, 2010).

The data compiled for EMF-22 share many of the data sources and methods EPA employed in this report for CH_4 and N_2O. SAP 2.1 presents 15 scenarios that make different assumptions about (among other things) economic and population growth rates, energy sources, environmental policies, and future technologies. This report uses the three reference scenarios in the comparison table below. The EDGAR 4.1 estimates emissions by country and source applying technology-based emission factors that take into account assumptions for country-specific activity data and abatement technologies. For EMF-22 and CCSP SAP 2.1, minimum and maximum values of reference scenarios are compared against, which varies by model. Although there are differences among individual numbers, the trends and relative magnitudes are similar.

[6] Used "Reference" scenario for all models, which include ETSAP-TIAM, FUND, GTEM, MERGE Optimistic, MERGE Pessimistic, MESSAGE, MiniCAM – BASE, MiniCAM - Lo Tech, POLES, SGM, and WITCH.

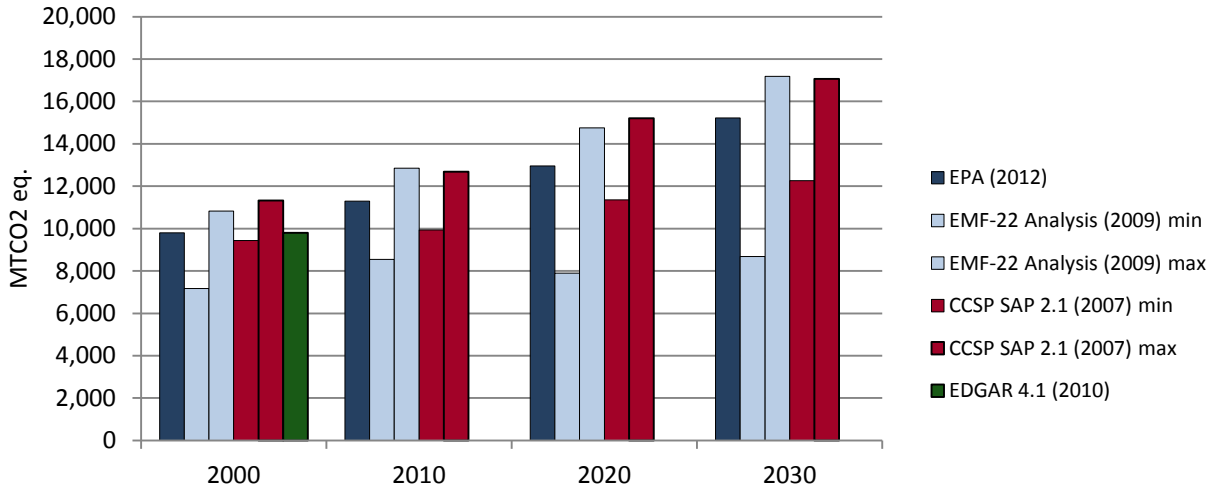
[7] Ranges depicted include estimates for the three reference scenarios, IGSM, MERGE, and MINICAM.

Table 2-2: Comparison of non-CO_2 Emission Estimates in this Report (EPA 2011) to Other Global Inventories ($MTCO_2e$)

Source	2000	2010	2020	2030
EPA (2012)	9,896	11,387	13,122	15,434
EMF-22 (2009)[a]	7,164-10,826	8,538-12,857	7,891-14,758	8,685-17,188
CCSP SAP 2.1 (2007)[b]	9,438-11,327	9,939-12,687	11,348-15,205	12,268-17,064
EDGAR 4.1 2010[c]	9,804[d]	NE	NE	NE

Codes: NE indicates "not estimated."
Notes:
[a] Energy Management Forum 22 (EMF-22) Analysis (EMF-22, 2009).
[b] CCSP Synthesis and Assessment Product 2.1 - Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (CCSP, 2007) – Ranges depicted include estimates for the three reference scenarios (IGSM, MERGE, and MINICAM)
[c] Emission Database for Global Atmospheric Research (EDGAR) 4.1 (EC-JRC, 2010).
[d] 97 metric tons of C_7F_{16} not included in total; unknown GWP.

Exhibit 2-5: Comparison of non-CO_2 Emission Estimates in EPA (2012) to Other Global Inventories ($MTCO_2e$)



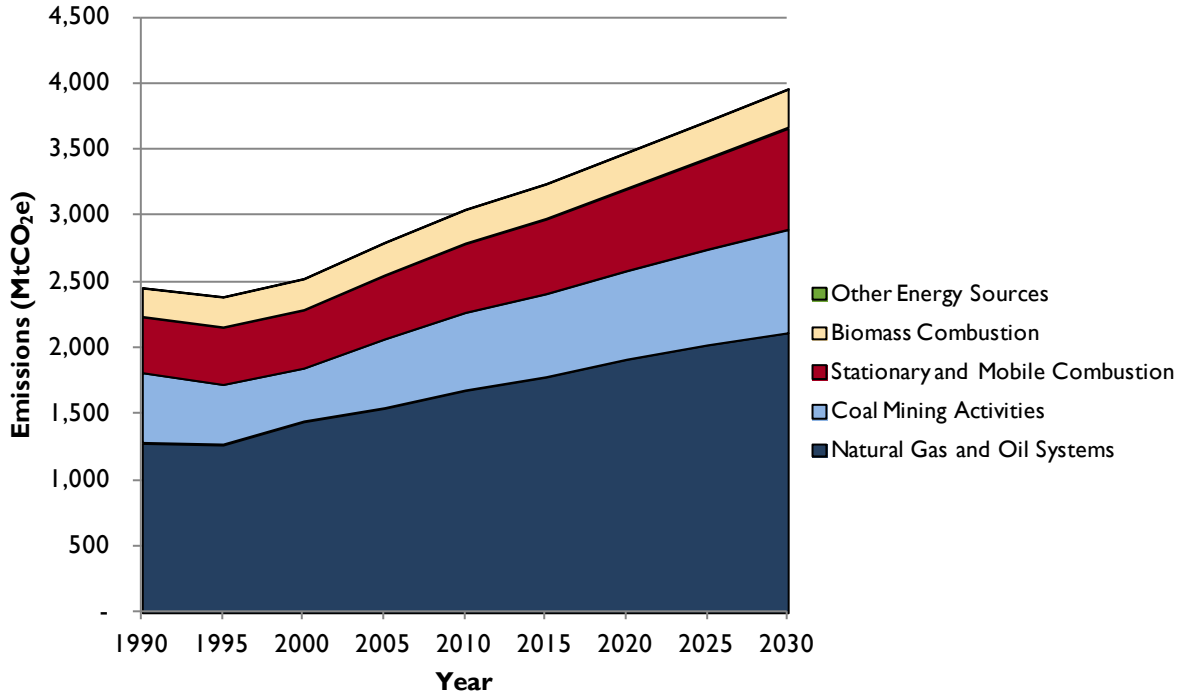
3 Energy

This chapter presents global CH_4 and N_2O emissions for 1990 to 2030 for the following energy sector sources:

- Natural Gas and Oil Systems (CH_4)
- Coal Mining Activities (CH_4)
- Stationary and Mobile Combustion (CH_4, N_2O)
- Biomass Combustion (CH_4, N_2O)
- Other Energy Sources (CH_4, N_2O), including:
  - Waste Combustion (CH_4, N_2O)
  - Fugitives from Solid Fuels (N_2O)
  - Fugitives from Natural Gas and Oil Systems (N_2O)

The energy sector is the second largest contributor to global emissions of non-CO_2 greenhouse gases, accounting for 26 percent of emissions in 2005. In 1990, the energy sector accounted for about 2,500 $MtCO_2e$ of non-CO_2 GHG emissions. Between 1990 and 2005, non-CO_2 emissions from the energy sector have grown 14 percent, to about 2,800 $MtCO_2e$. Emissions from this sector are projected to further increase 42 percent by 2030 to about 4,000 $MtCO_2e$. Exhibit 3-1 shows energy sector emissions by source. Fugitive emissions from natural gas and oil systems are the largest source of non-CO_2 GHG emissions from the energy sector, accounting for 55 percent of energy-related emissions in 2005. The next largest source in this sector is emissions from coal mining activities, accounting for 19 percent of energy related emissions in that year.

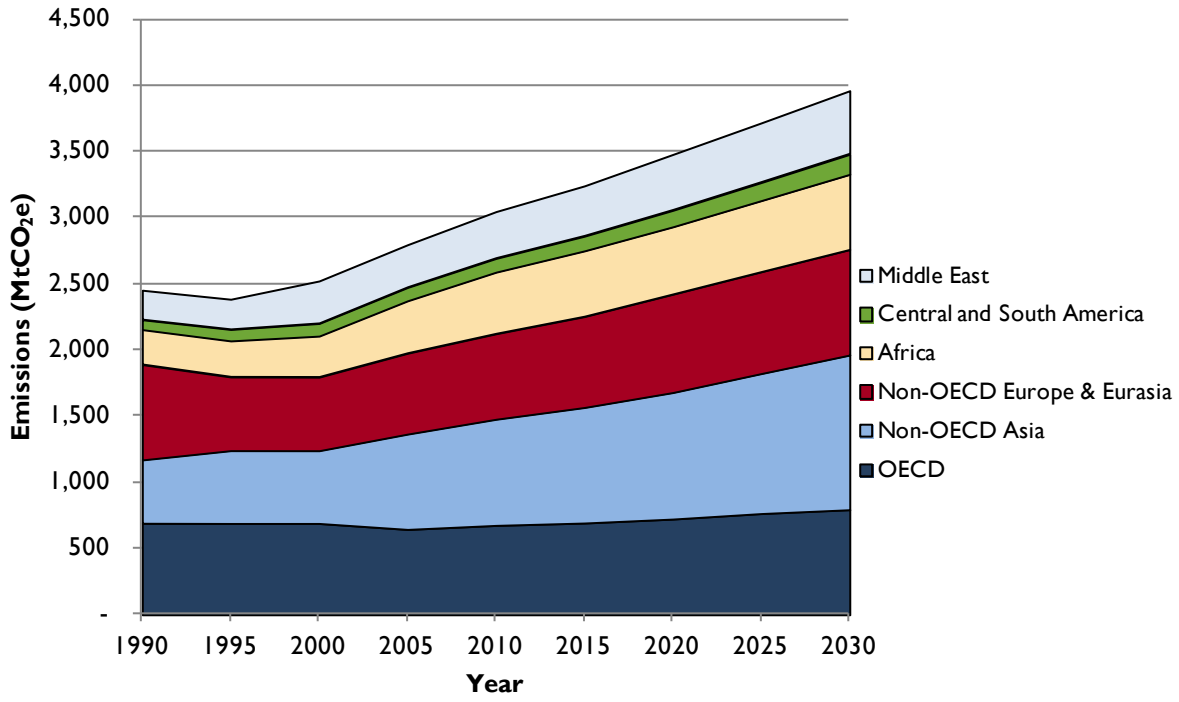
Exhibit 3-1: Total Non-CO_2 Emissions from the Energy Sector, by Source ($MtCO_2e$)



Several key factors play a role in emission trends from the energy sector as a whole: economic restructuring in Eastern Europe and the Former Soviet Union (FSU), and several key coal mining countries; a shift from coal to natural gas as an energy source in several regions; and expansive growth in energy consumption in less developed regions. These effects are further discussed within each source discussion.

Exhibit 3-2 displays energy sector emissions by region. In 1990, the regions with the most emissions were non-OECD Europe and Eurasia and the OECD, accounting for 29 percent and 28 percent respectively of global energy emissions. Between 1990 and 2005, this pattern shifted, however, as emissions declined in these two regions while increasing in other regions. In 2005, non-OECD Asia accounted for 26 percent of global energy emissions. Emissions in all regions are expected to increase over the projection period of 2005 to 2030, but emissions from non-OECD Asia, Africa, and Central and South America will grow more quickly than non-OECD Europe and Eurasia or OECD regions.

Exhibit 3-2: Total Non-CO_2 Emissions from the Energy Sector, by Region ($MtCO_2e$)



3.1 Natural Gas and Oil Systems (CH_4)

3.1.1 Source Description

CH_4 is the principal component of natural gas (95 percent 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 CH_4 in significant quantities since natural gas is often found in conjunction with petroleum deposits. In both oil and natural gas systems, CH_4 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.

Emissions calculations for this source utilize international statistics on production and consumption of natural gas and oil. Default emission factors relate emissions to energy product flows through different industry segments. Default emission factors differ between developed and developing countries.

The emissions projections presented in this report rely on IPCC Tier 1 calculations and country-reported inventory data. In the case of U.S. emissions estimates, this report relies on emissions estimates from the 2011 U.S. GHG Inventory. For the natural gas sector emissions estimates in particular, EPA received information and data from stakeholders related to the estimates, is carefully evaluating all relevant information provided, and is preparing to update the GHG Inventory methodology based on this information. The upcoming 2013 Inventory will have significant methodological updates, particularly for the production segment, and these updates will lead to revised emission estimates for the U.S. Future trends in U.S. emissions from natural gas and oil systems are based on projections in the 2010 U.S. Climate Action Report. Since that time, new

regulations have been implemented which will result in lower emissions from this source in the U.S.. New U.S. non-CO_2 projections are being prepared which will be published as part of the next U.S. Climate Action Report in January, 2014.

International voluntary programs encourage measures which can reduce CH_4 emissions without reducing energy production, but those mitigation programs are not explicitly included in the estimates. Mitigation measures include installing equipment designed to minimize CH_4 emissions, retrofitting existing equipment and conducting inspection and maintenance regimes to identify, quantify and repair leaks.

3.1.2 Source Results

Between 1990 and 2005, global CH_4 emissions from natural gas and oil systems are estimated to have increased by about 21 percent, from 1,278 to 1,543 $MtCO_2e$ (see Table 3-1). Underlying this trend have been increases in natural gas and oil production. Over this time period, emissions have declined modestly in OECD countries (see Exhibit 3-3). Emissions declined in non-OECD Europe and Eurasia between 1990 and 1995, but have risen gradually since then. Significant percentage increases in emissions have occurred in other regions, especially in Africa and the Middle East, where emissions nearly doubled between 1990 and 2005.

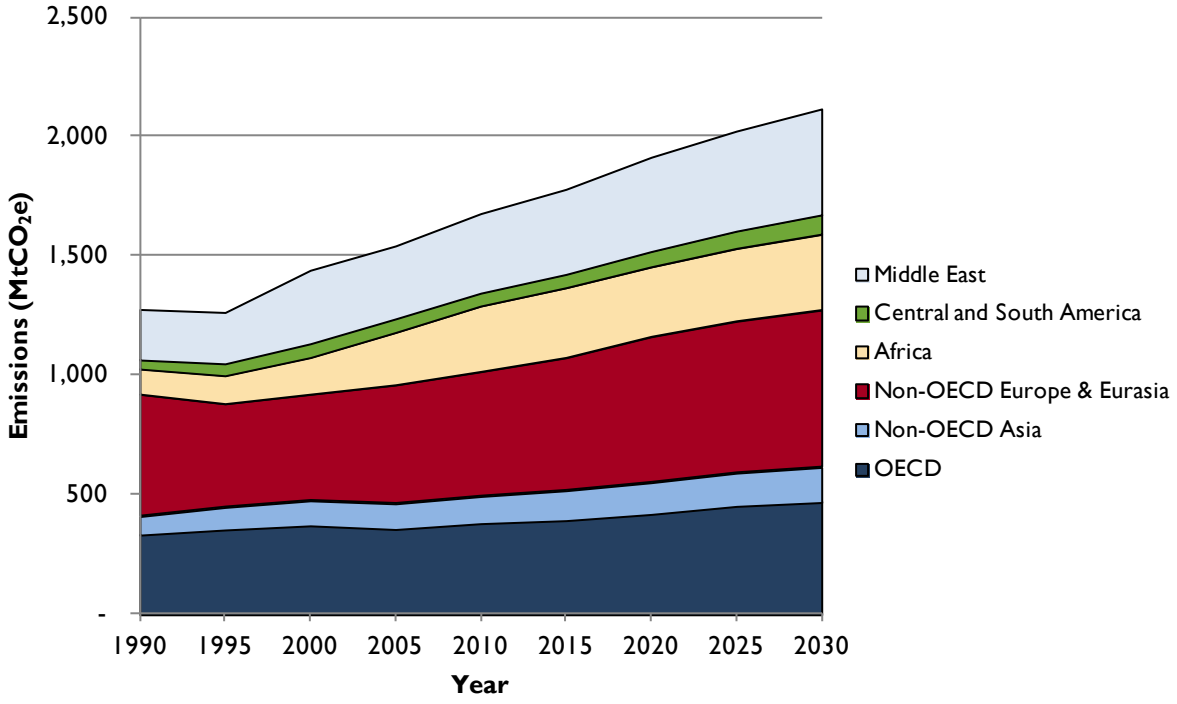
From 2005 to 2030, emissions are projected to increase by 31 percent, from 1,543 to 2,021 $MtCO_2e$. This projection corresponds to increases in natural gas and oil production from 2005 to 2030. Emissions are expected to increase in all regions. Emissions from non-OECD regions are expected to grow about twice as fast as those from the OECD over the projection period.

Emissions in OECD countries are expected to grow more slowly from 2005 to 2030 than emissions in non-OECD regions. Natural gas production is expected to increase in countries such as the United States and Australia, whereas production is expected to decline in European OECD countries. In the United States, advances in production technology have allowed exploitation of vast shale gas reserves to production. By contrast, in Europe production of tight gas, shale gas, and coalbed CH_4 are not sufficient to offset declining production. Most oil production has already matured in the OECD. However, it is expected to increase in the U.S. and Canada because of expanded use of enhanced oil recovery and unconventional production such as from oil sands. Increasing consumption of natural gas also contributes to future increases in emissions from natural gas and oil systems in the OECD countries. (EIA, 2009)

Table 3-1: Total CH_4 Emissions from Natural Gas and Oil Systems ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	1,278.3	1,265.8	1,441.5	1,542.7	1,677.3	1,778.3	1,911.8	2,020.6	2,112.9

Exhibit 3-3: CH_4 Emissions from Natural Gas and Oil Systems 1990 – 2030 ($MtCO_2e$)



Non-OECD Europe and Eurasia emit more from this source than any other region, and are expected to grow 33 percent from 2005 to 2030. Russia accounts for most natural gas production in this region, and has larger reserves of natural gas than any other country in the world. Production of natural gas and oil in Russia is expected to increase, driving emissions to increase 31 percent in this region from 1990 through 2030.

In the Middle East and Africa, emissions have grown by 44 percent and 107 percent from 1990 to 2005, respectively. Natural gas consumption has increased substantially in recent years. Consumption is expected to continue to grow, but not as quickly as in recent years. The Middle East accounts for 40 percent of proved natural gas reserves, and future production increases are expected in the Middle East and Africa. (IEO, 2010)

The largest natural gas consumption increases are expected in non-OECD Asia, particularly in China and India. Natural gas consumption is also growing quickly in Central and South America. (IEO2010) This growth partially accounts for expected emissions growth of 37 percent in this region, from 2005 to 2030.

Actual future emissions may differ from these projections for several reasons. Efforts are underway to modernize gas and oil facilities in Russia and many Eastern European countries, which could help reduce fugitive emissions. In areas where gas production is projected to increase, emissions will not necessarily increase at the same rate. As the world becomes more concerned with the emissions of greenhouse gases, new legislation and voluntary carbon markets are developing to increase energy production efficiency in the natural gas and oil industry. Projections of oil and natural gas production and consumption are, by nature, highly uncertain. The uncertain future of gas prices adds an additional level of uncertainty.

Current emissions calculations are based on quantity of oil and gas production and consumption. However, leakage and venting do not necessarily increase linearly with throughput, and newer equipment tends to leak less than older equipment. More accurate estimation methodologies would make use of counts of equipment and country-specific emission factors, but such information is not readily available for many countries. Even when more accurate methodologies are used, estimates for this source have significant uncertainty. Some of the Tier 1 emissions factors provided in the 2006 IPCC guidelines for this source have very large uncertainty ranges. Where the guidelines have only provided a range, but no central estimate, we have used the midpoint of the range as the emissions factor. The country-by-country results for this source reveal significant discrepancies based on differences in methodology (e.g., tier 1 calculation versus country-reported data) and among countries with reported data, discrepancies based on choice of emissions factor.

3.2 Coal Mining Activities (CH_4)

3.2.1 Source Description

CH_4 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. CH_4 is produced during the process of coalification, where vegetation is converted by geological and biological forces into coal. Because CH_4 is explosive, it must be removed from underground mines high in CH_4 as a safety precaution.

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 CH_4 content. Coals such as anthracite and semianthracite have the highest coal ranks, while peat and lignite have the lowest. Pressure increases with depth and prevents CH_4 from migrating to the surface and, as a result, underground mining operations typically emit more CH_4 than surface mining (EPA, 1993). In addition to emissions from underground and surface mines, post-mining processing of coal and abandoned mines also release CH_4.[1]

Emissions calculations for this source use international statistics on production of hard coal and lignite, which are assumed to correspond to underground and surface mining, respectively. Default emission factors are used which relate the quantity of coal mined to CH_4 emissions. Abandoned mines are not considered in this analysis due to a lack of data.

Voluntary programs encourage capture and utilization of coalbed CH_4. The value of captured methane is dependent on proximity to an end user or pipeline and the quality of gas extracted. This analysis accounts for some CH_4 recovery and use, although not all coal mine CH_4 projects may be accounted for (please see Section 7.1.2). The projection assumes that mitigation activities will continue in the countries where coal mine methane projects have been documented.

[1] While emissions from abandoned coal mines were not explicitly estimated in this report, some countries report emissions from abandoned mines within this source category. In these cases, this source category includes these emissions.

3.2.2 Source Results

As shown in Table 3-2, global CH_4 emissions from coal mining are estimated to have decreased by 2 percent, from 530 $MtCO_2e$ to 522 $MtCO_2e$between 1990 and 2005. Over this time period, total primary coal production has increased. In 2005, coal mine methane projects in 12 countries prevented emissions of about 35 $MtCO_2e$, accounting for part of this divergence. The geographic dispersion of emissions has shifted over the historical period between regions. Coal mine CH_4 emissions have declined in the OECD, non-OECD Europe and Eurasia, while they have increased in non-OECD Asia. Emissions in the Middle East, Africa, and Central and South America are small compared to the other regions.

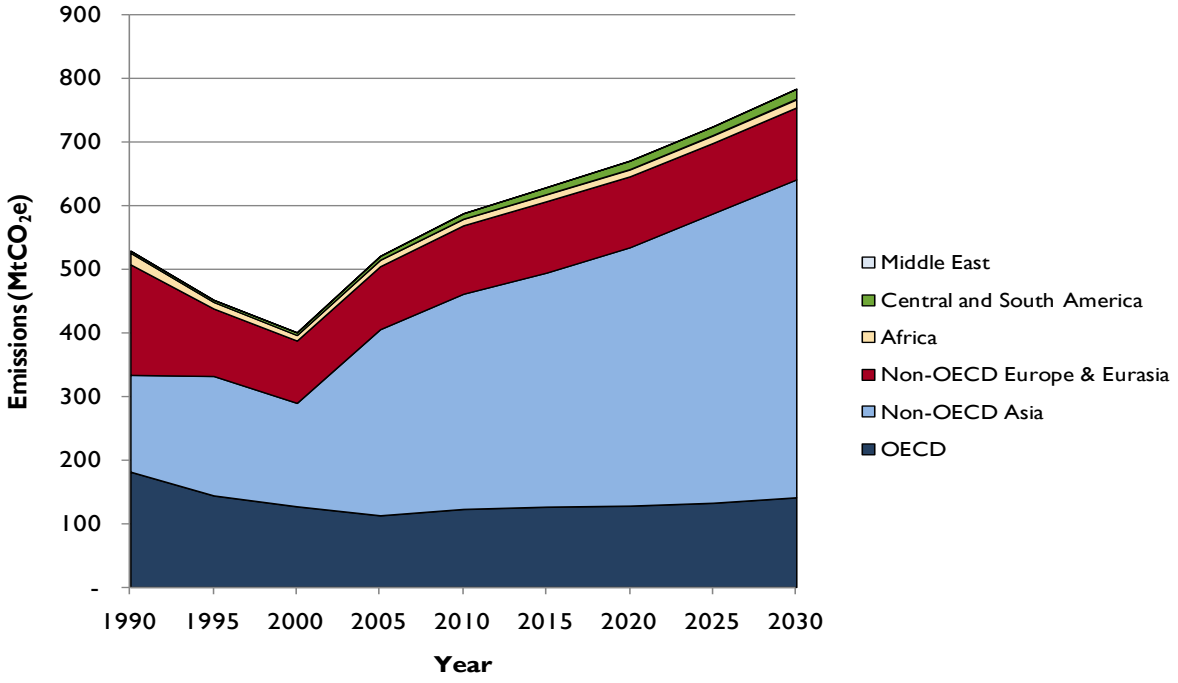
From 2005 to 2030, CH_4 emissions from coal mines are projected to increase by 50 percent, from 522 $MtCO_2e$ to 784 $MtCO_2e$. This projection assumes significant increases in coal production by 2030. While emissions in all regions are expected to increase, the rise in emissions is expected to be much more significant in some regions than in others. Emissions in non-OECD Asia are expected to increase relatively more quickly than in OECD and non-OECD Europe and Eurasia over the projection period.

The non-OECD Asia region's CH_4 emissions from coal mining have nearly doubled between 1990 and 2005, and are expected to increase by about 71 percent by 2030. This region includes China, which has extensive coal resources and coal mining. China is expected to account for a majority of the increase in world coal production over the projection period. The Chinese economy is growing quickly and much of the increased electric power and industrial demand will be met by coal. The decrease in coal mining CH_4 emissions from 1995 to 2000 is caused primarily by mine closures and a significant reduction in coal production during this time period.[2] Between 1998 and 2002, the government of China closed tens of thousands of small mines (Andrews-Speed et al, 2005). While EPA's methodology captures the impact of these closures on overall production, the methodology does not distinguish between mining at large and small mines. It is unclear how emissions intensity may differ at various types of mines, and the extent to which production shifted from small to large mines. Moreover, EPA does not estimate emissions from abandoned mines, so emissions resulting from these closures are not reflected in the estimates. China and India, among other countries, have extensive uncontrolled fires in their coal mining regions which may add to fugitive emissions, but are not included in the estimates (Stracher and Taylor, 2004).

Table 3-2: Total CH_4 Emissions from Coal Mining Activities ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	529.8	452.6	401.4	521.6	588.6	629.7	671.4	725.3	784.3

Exhibit 3-4: CH_4 Emissions from Coal Mining Activities 1990 – 2030 ($MtCO_2e$)



The OECD experienced a significant decrease in emissions from 1990 to 2005. In the 1990s, coal production declined rapidly in United Kingdom and Germany, contributing substantially to the reduction in OECD emissions from 1990 to 2005. Emissions for those countries are expected to continue to decrease at a slower rate, and to begin leveling off around 2010. Emissions for the OECD overall, however, are expected to increase between 2005 and 2030, partly due to an increasing trend for the United States and Australia. While emissions from coal mining activities in the U.S. decreased between 1900 and 2005, they are projected to follow an increasing trend after 2005.

The non-OECD Europe and Eurasia region also experienced a significant decrease in emissions between 1990 and 2005, although emissions began rising again after 2000. In Russia and in Eastern European coal producing countries, restructuring of the energy industries caused many of the gassiest underground mines to close during the 1990s resulting in the decrease in emissions. Emissions in this region are expected to increase through 2015, at which point they expected to begin to level off.

Reductions due to CH_4 recovery and use of coal mine CH_4 will likely impact future emission estimates. Reductions from coal mine CH_4 projects could help slow or even decrease, emissions for some countries even when coal production increases. Projecting the abatement due to future coal mine CH_4 projects is challenging (please see Section 7.1.2 for a discussion of how EPA has accounted for some coal mine CH_4 projects, and areas of uncertainty from such projects).

Emissions calculations in this section are based on coal production statistics, divided into hard coal and lignite production. However, CH_4 emissions are not necessarily directly related to production. CH_4 emissions occur not just 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.

3.3 Stationary and Mobile Combustion (CH_4, N_2O)

3.3.1 Source Description

N_2O is a product of the reaction between nitrogen and oxygen during combustion of fossil fuels. Both mobile and stationary sources emit N_2O, and the volume emitted varies according to the type of fuel, combustion technology, size and vintage (model year for mobile combustion), pollution control equipment used, and maintenance and operating practices. Stationary and mobile combustion also result in CH_4 emissions and are primarily a function of the CH_4 content of the fuel and the combustion efficiency. However, combustion is a relatively minor contributor to overall CH_4 and N_2O emissions, representing just over 3 percent and 8 percent of global CH_4 and N_2O emissions in 2005, respectively.

Mobile combustion sources such as automobiles and airplanes emit N_2O as an exhaust emission from a variety of engine and fuel configurations. As with stationary sources, N_2O emissions are closely related to air-fuel mixtures and combustion temperature, as well as pollution control equipment on transportation vehicles. Key factors affecting fuel consumption and, ultimately emissions, for mobile sources include the distance traveled for vehicles, hours of operation for off-road equipment, age of vehicles, and mode of operation. Road transport accounts for the majority of mobile source fuel consumption, and as a result, the majority of mobile N_2O emissions.

3.3.2 Source Results

Between 1990 and 2005, CH_4 and N_2O emissions from stationary and mobile have increased 14 percent, from 423 $MtCO_2e$ to 480 $MtCO_2e$ (Table 3-3). Total fossil fuel consumption has increased over this time period. Emissions have decreased about 2 percent in OECD countries and by 15 percent among EU countries, while they have increased in other regions.

From 2005 to 2030, CH_4 and N_2O emissions from stationary and mobile combustion are projected to increase 59 percent, from 480 $MtCO_2e$ to 765 $MtCO_2e$. This projection assumes steady increase in fossil fuel consumption over the projection period. Emissions are expected to increase in all regions except the OECD. CH_4 and N_2O emissions from combustion are expected to double in non-OECD Asia during the projection period. The results for stationary and mobile combustion are shown in Table 3-3, Exhibit 3-5, and Exhibit 3-6.

The increasing emissions in non-OECD Asia are driven by higher demand for and production of energy and the increased use of automobiles. China and India are the main drivers of growth in this region, and their emissions are expected to grow by 89 percent and 127 percent respectively in the projection period.

In OECD countries, CH_4 and N_2O emissions from stationary and mobile combustion have historically declined despite increasing energy use. This has been achieved through improvements in combustion technologies and pollution controls. Unlike CO_2 emissions, CH_4 and N_2O emissions from combustion are highly dependent upon combustion conditions and not directly proportional to fuel quantities combusted. Emissions in the OECD are expected to continue to decline despite increasing energy use.

Table 3-3: CH_4 and N_2O Emissions from Stationary and Mobile Combustion ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	221.3	212.0	205.4	224.3	242.4	264.4	291.0	323.4	362.9
N_2O	201.3	221.1	234.6	256.1	277.4	299.9	327.0	360.8	402.5
Total	**422.6**	**433.1**	**439.9**	**480.4**	**519.8**	**564.2**	**618.1**	**684.2**	**765.4**

Exhibit 3-5: CH_4 Emissions from Stationary and Mobile Combustion 1990-2030 ($MtCO_2e$)

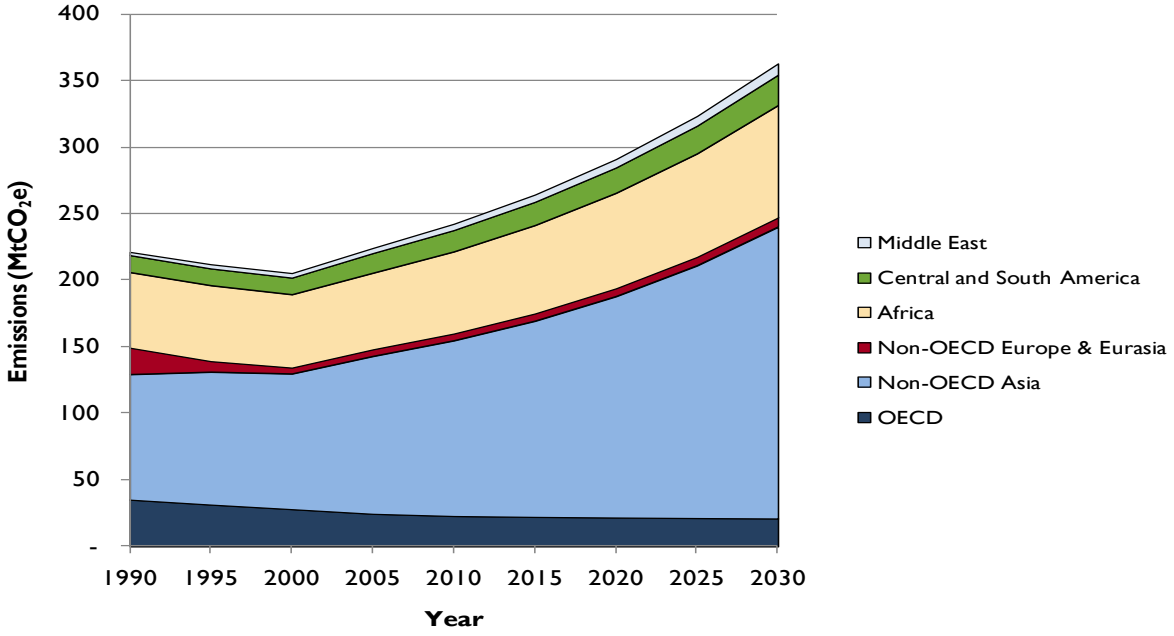
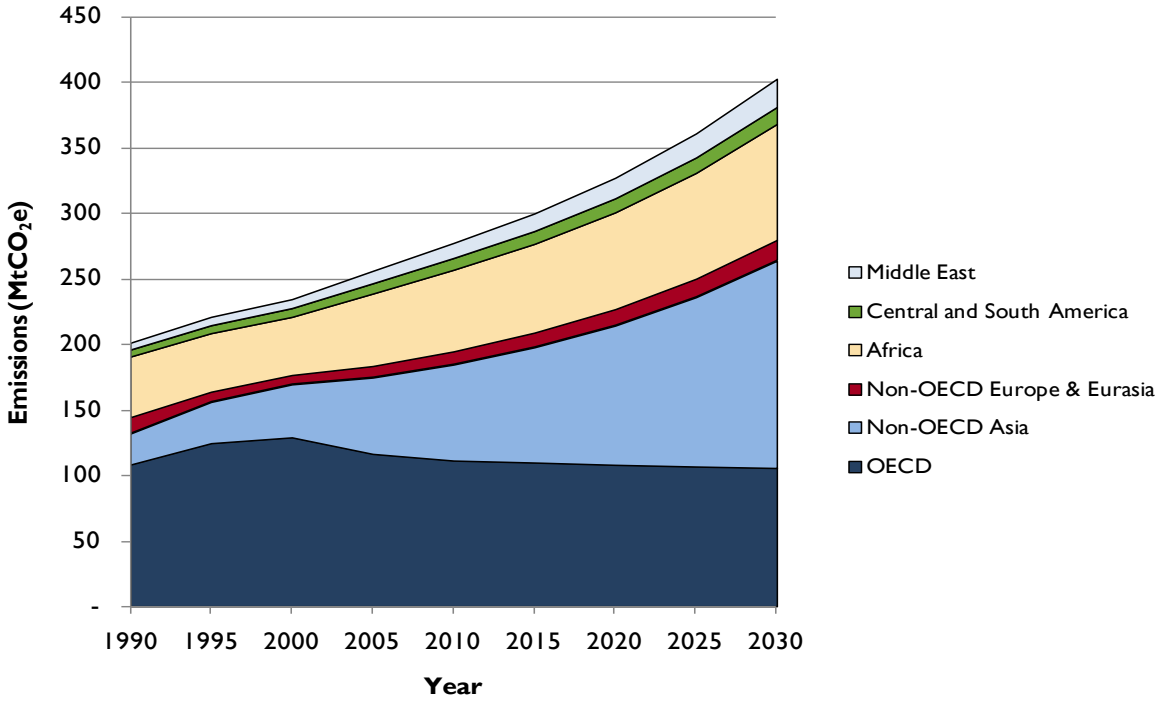


Exhibit 3-6: N_2O Emissions from Stationary and Mobile Combustion 1990-2030 ($MtCO_2e$)



3.4 Biomass Combustion (CH_4, N_2O)

3.4.1 Source Description

CH_4 and N_2O are produced as a result of incomplete biomass combustion. Fuel wood, charcoal, agricultural residues, agricultural waste, and municipal waste combustion are the major contributors to CH_4 and N_2O emissions within this category. Biomass combustion in developing countries often refers to the combustion of biofuels in small-scale combustion devices for heating, cooking, and lighting purposes. In general, for developing countries the combustion of biomass in the residential sector is the leading contributor of emissions for this source. In developed countries, biomass combustion primarily refers to the combustion of biofuels in large-scale industrial processes (e.g., wood and wood products, pulp and paper), and to a lesser extent, in residential applications. Because of the wide variety in the types and conditions under which these fuels are burned, estimates for this category are highly uncertain and difficult to predict.

3.4.2 Source Results

Between 1990 and 2005, CH_4 and N_2O emissions from biomass combustion are estimated to have increased by 13 percent, from 217 to 246 $MtCO_2e$ (Table 3-4). Over this time period, underlying biomass combustion grew on an energy content basis. Liquid biofuel use has grown quickly, but remains smaller than solid biomass or charcoal usage, which grew more slowly. Greenhouse gas emissions from biomass combustion have grown significantly in Africa, while they have grown more slowly in Central and South American and non-OECD Asia and declined in the OECD and non-OECD Europe and Eurasia.

As shown in Exhibit 3-7 and Exhibit 3-8, CH_4 and N_2O emissions from biomass combustion are projected to increase by 18 percent from 2005 to 2030, from 246 to 290 $MtCO_2e$. Underlying biomass usage is assumed to increase over the same time period. Biomass combustion emissions are expected to increase most quickly in OECD countries, while biomass emissions in other regions grow more slowly. In OECD countries, projected emissions increase as a result of a projected threefold increase in biomass use for combined heat and power production and in electricity-only power plants (IEA, 2009). Despite being one of the largest contributors, total biomass emissions in the non-OECD Asia region are projected to remain essentially flat between 2005 and 2030 due to a decrease in biomass consumption in the residential sector. This decline is a result of the increased industrialization in the region, and fuel switching from biomass to fossil fuels. The non-OECD Asia region is set to play an increasingly important role in global energy markets as energy consumption on a whole is projected to grow rapidly due to rapid economic and population growth, and continuing urbanization and industrialization (IEA, 2009).

Table 3-4: Total CH_4 and N_2O Emissions from Biomass Combustion ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	176.3	184.6	189.1	198.0	204.4	209.9	216.1	222.9	230.4
N_2O	40.6	43.0	44.9	47.6	50.1	52.1	54.3	56.7	59.4
Total	**217.0**	**227.6**	**234.0**	**245.5**	**254.5**	**262.0**	**270.4**	**279.6**	**289.9**

Exhibit 3-7: CH_4 Emissions from Biomass Combustion 1990 – 2030 ($MtCO_2e$)

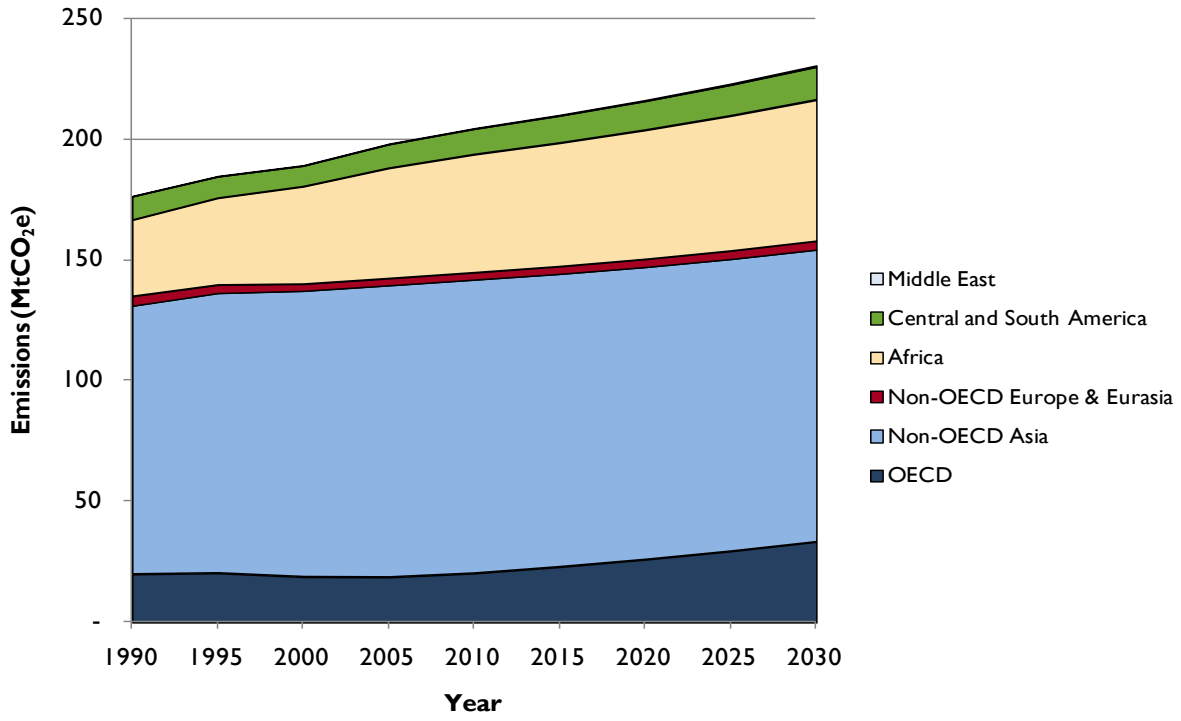
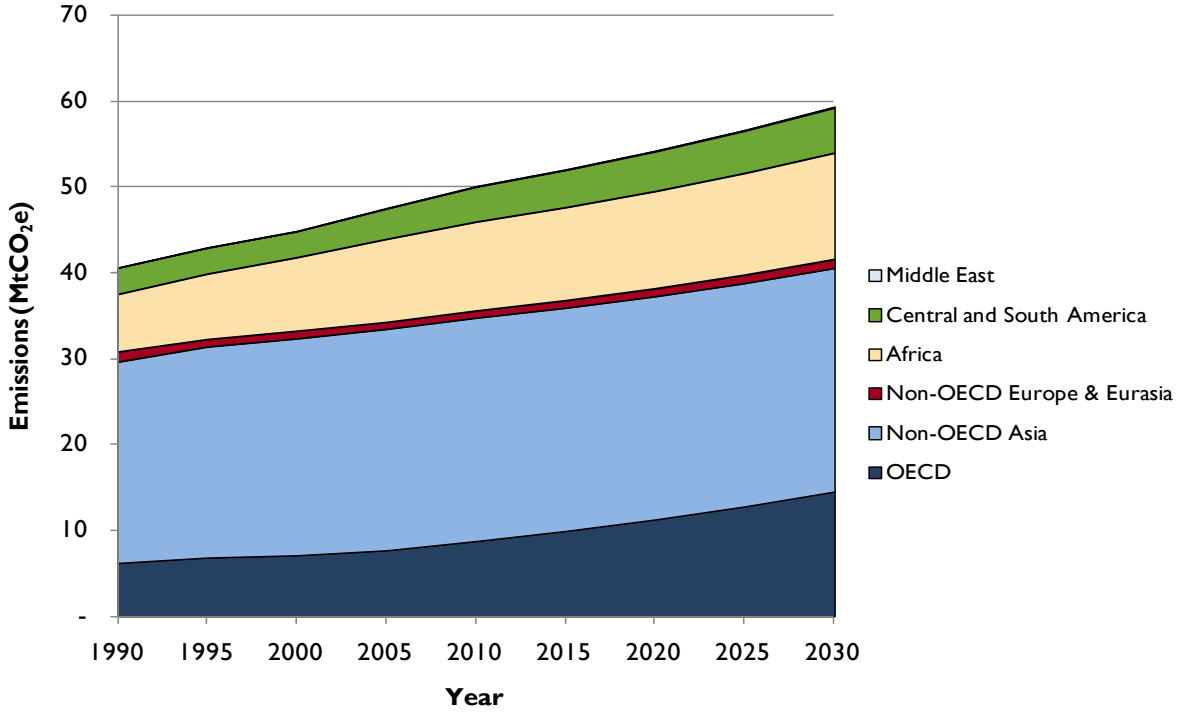


Exhibit 3-8: N_2O Emissions from Biomass Combustion 1990 – 2030 ($MtCO_2e$)



3.5 Other Energy Sources (CH_4, N_2O)

3.5.1 Source Description

This category includes emissions from the energy sector that contribute only a small fraction of total overall emissions, but are reported by specific countries to the UNFCCC and are thus grouped together in this report. The data presented here include the following three sources of CH_4 and N_2O:

- Waste Combustion (CH_4,N_2O)
- Fugitives from Solid Fuels (N_2O)
- Fugitives from Natural Gas and Oil Systems (N_2O)

3.5.2 Source Results

The results for this source are presented in Table 3-5. The OECD is by far the largest contributor to this category, accounting for an average of 95 percent of emissions from 1990 through 2030. The data presented in Table 3-5, are not fully comparable to data in the remainder of this report. Emissions are included only for those countries which reported emissions, as opposed to other sources which use a combination of calculated and country-reported data. Please see the methodology section for further discussion of this source category.

Table 3-5: Total CH_4 and N_2O Emissions from Other Energy Sources ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
N_2O	2.6	3.1	3.4	3.5	3.4	3.4	3.4	3.4	3.4
Total	**3.1**	**3.7**	**3.9**	**4.1**	**3.9**	**3.9**	**3.9**	**3.9**	**3.9**

Exhibit 3-9 and Exhibit 3-10 illustrate trends in CH_4 and N_2O emissions for this source category.

Exhibit 3-9: CH_4 Emissions from Other Energy Sources 1990 – 2030 ($MtCO_2e$)

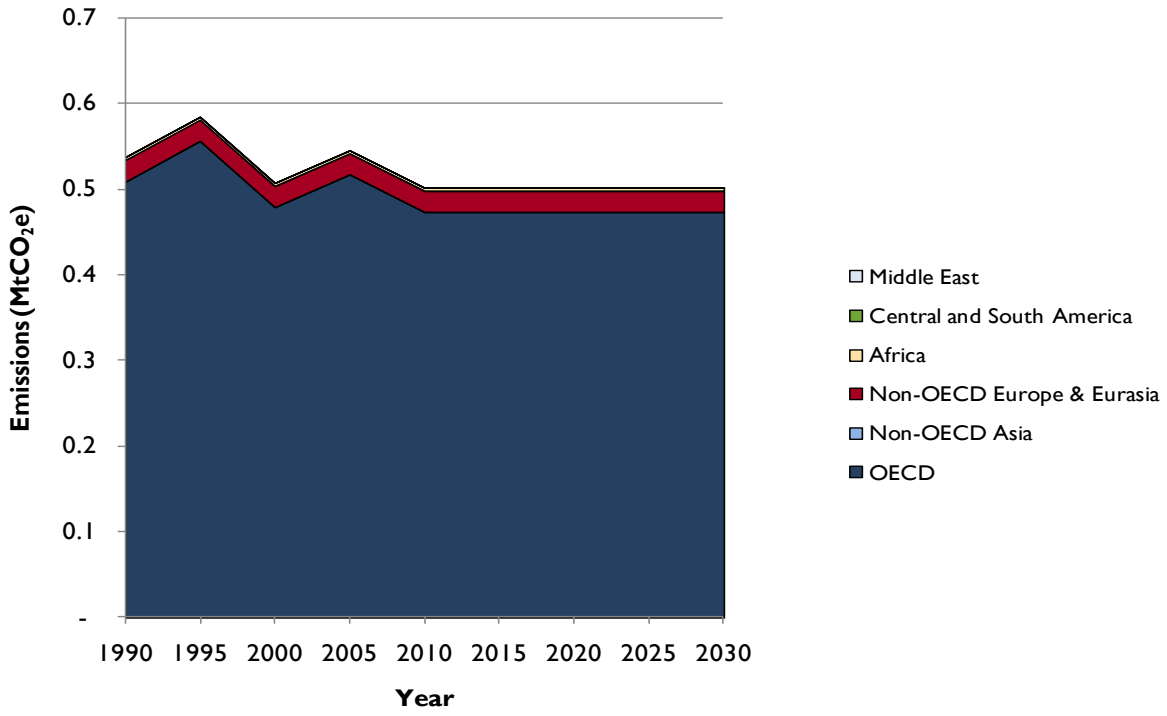
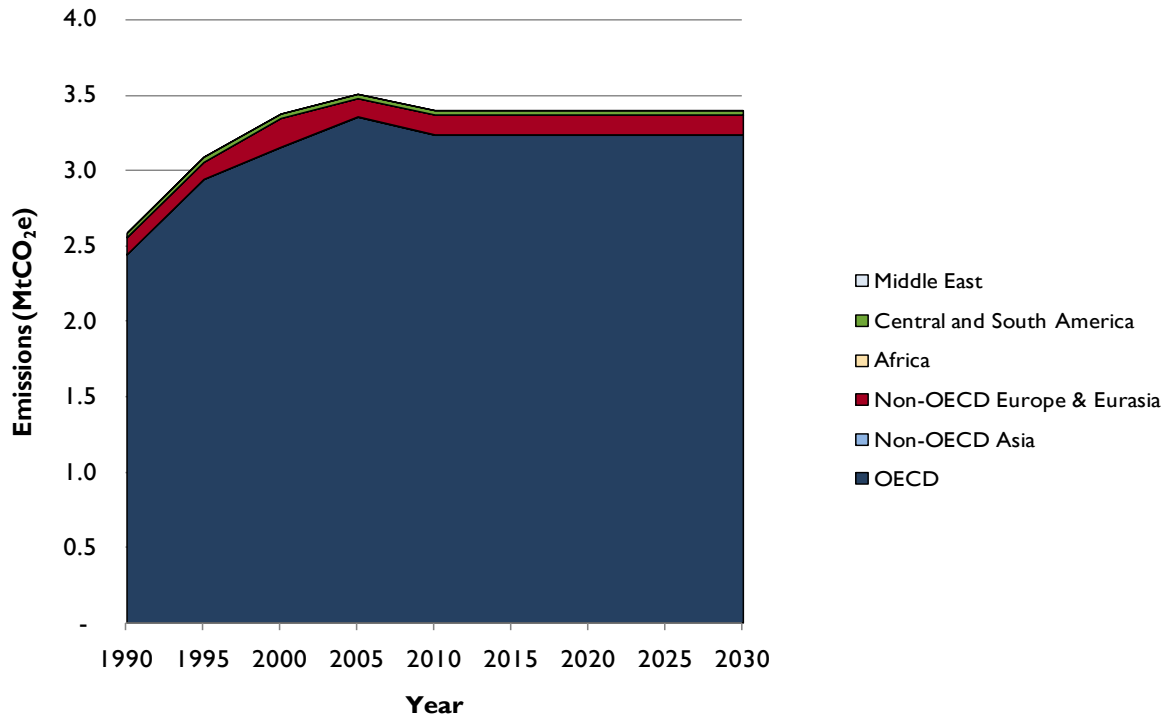


Exhibit 3-10: N_2O Emissions from Other Energy Sources 1990 – 2030 ($MtCO_2e$)



4 Industrial Processes

This section presents non-CO_2 emissions from the industrial processes sector for 1990 to 2030. The industrial processes sector includes industrial sources of N_2O and CH_4, along with several sources of F-GHGs. F-GHG emissions covered in this section include HFCs used as substitutes for ozone-depleting substances (ODSs) and industrial sources of HFCs, PFCs, and SF_6. Initial estimates of NF_3 emissions from electronics manufacturing processes are also included as new sources in this update. The categories and their GHG emissions presented in this section are as follows:

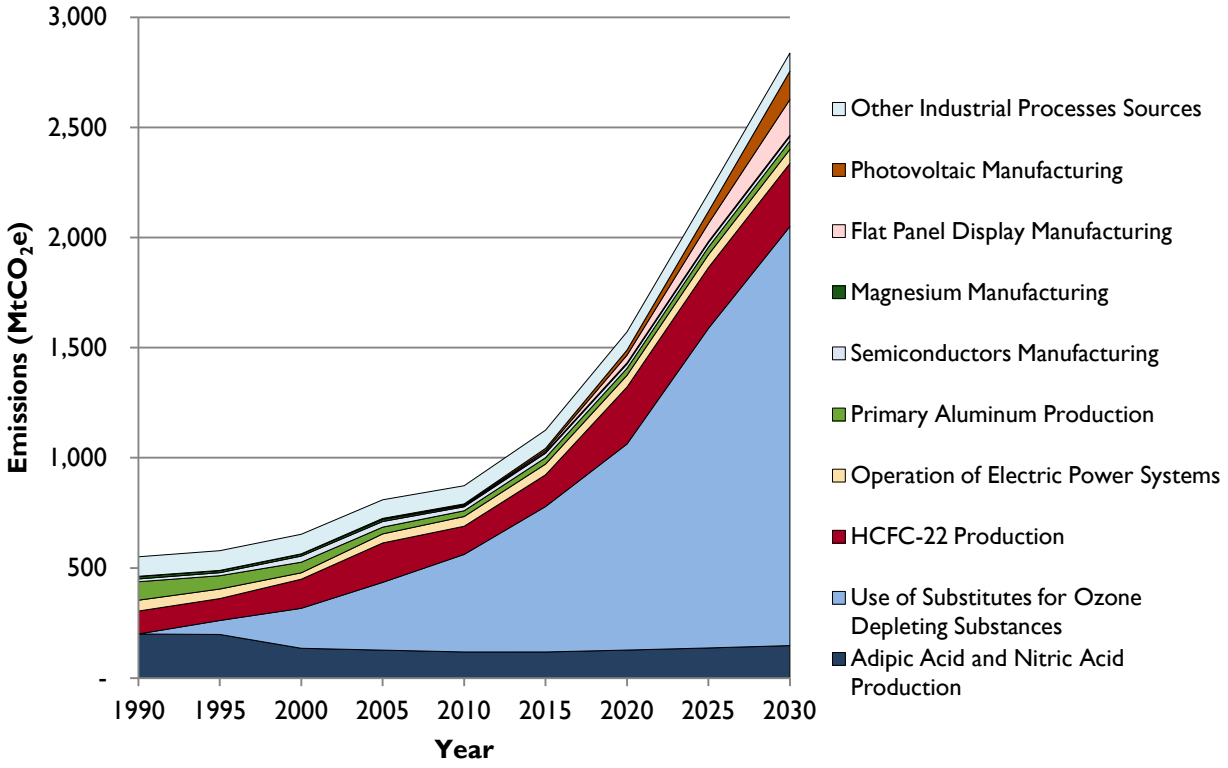
- Adipic Acid and Nitric Acid Production (N_2O)
- Use of Substitutes for Ozone-Depleting Substances (HFCs)
- HCFC-22 Production (HFCs)
- Electric Power Systems (SF_6)
- Primary Aluminum Production (PFCs)
- Magnesium Manufacturing (SF_6)
- Semiconductor Manufacturing (HFCs, PFCs, SF_6)
- Flat Panel Display Manufacturing (PFCs, SF_6)
- Photovoltaic Manufacturing (PFCs, NF_3)
- Other Industrial Processes Sources (CH_4, N_2O), including:
    - 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)

The industrial processes sector was the smallest contributor to global emissions of non-CO_2 greenhouse gases in 1990, accounting for only 6 percent of total emissions, but it has also grown the fastest of all sectors. Between 1990 and 2005, non-CO_2 GHG emissions from industrial processes grew by 47 percent, and accounted for 8 percent of global emissions in 2005. Emissions are projected to grow even more quickly, nearly quadrupling between 2005 and 2030 to about 2,800 $MtCO_2e$ (18 percent of the global total). Exhibit 4-1 shows the industrial processes sector emissions by source. In 1990 and 1995, the largest source of non-CO_2 emissions from this sector was adipic acid and nitric acid production, which accounted for 36 percent of emissions in 1990. Between 1990 and 2005, HFC emissions of substitutes for ODSs and HFC-23 emissions from HCFC-22 production have become the most important sources within the sector. The increase in emissions of HFCs used as ODS substitutes corresponds to decreasing use of CFCs and HCFCs, which they

replace. CFCs and HCFCs are potent GHGs but, following international convention, their emissions are not included here.

By 2030, emissions from adipic and nitric acid production are projected to account for only 5 percent of the sector's emissions, due to the mitigation efforts begun in the 1990s as well as large increases in emissions from other sources.

Exhibit 4-1: Total Non-CO_2 Emissions from the Industrial Processes Sector, by Source ($MtCO_2e$)



During the 40-year period from 1990 to 2030, the replacement of ODSs with HFCs (and other substitutes) will lead to decreases in emissions of CFCs and HCFCs and increases in emissions of HFCs used as substitutes for ODSs. HFCs have a wide variety of applications, including use as refrigerants, aerosol propellants, solvents, foam blowing agents, medical sterilization carrier gases, and fire extinguishing agents. It should be noted that the ODSs themselves are greenhouse gases; however, following international conventions, the emissions of these substances are not included in the baseline emissions presented in this report. Only emissions of non-ozone-depleting fluorinated gases used as substitutes for ODSs are included in the baseline emissions. Had the phaseout of ODSs not occurred, more warming would have occurred because many ODSs are more potent GHGs than the HFCs and other substitutes now being used or introduced.

Emissions of HFCs used as substitutes for ODSs have grown dramatically between 1990 and 2005, from zero[1] to 308 $MtCO_2e$ (38 percent of sector total). HFC emissions from ODS substitutes are expected to increase by a factor of five between 2005 and 2030, driven by strong demand for

[1] In 1990, emissions for this category were negligible, with U.S. emissions accounting for less than 0.5 $MtCO_2e$.

refrigeration and air conditioning equipment in developing countries. Emissions from HCFC-22 production are projected to increase by 60 percent while emissions from magnesium manufacturing are projected to decrease 47 percent over this same time period.

Exhibit 4-2 displays industrial processes sector non-CO_2 emissions by region. In 1990, 69 percent of sector emissions were from the OECD region. However, emissions in the OECD have grown relatively slowly between 1990 and 2005, and now constitutes 54 percent of the sector total while emissions from non-OECD Asia now accounts for 25 percent of the global total. By 2030, the relative share of emissions from these two regions is expected to roughly switch. Non-OECD Asia is expected to account for 46 percent of emissions while the OECD is expected to account for 38 percent. This trend is largely due to projected increases in emissions from ODS substitutes and HCFC-22 production in China.

Exhibit 4-2: Total Non-CO_2 Emissions from the Industrial Processes Sector, by Region ($MtCO_2e$)

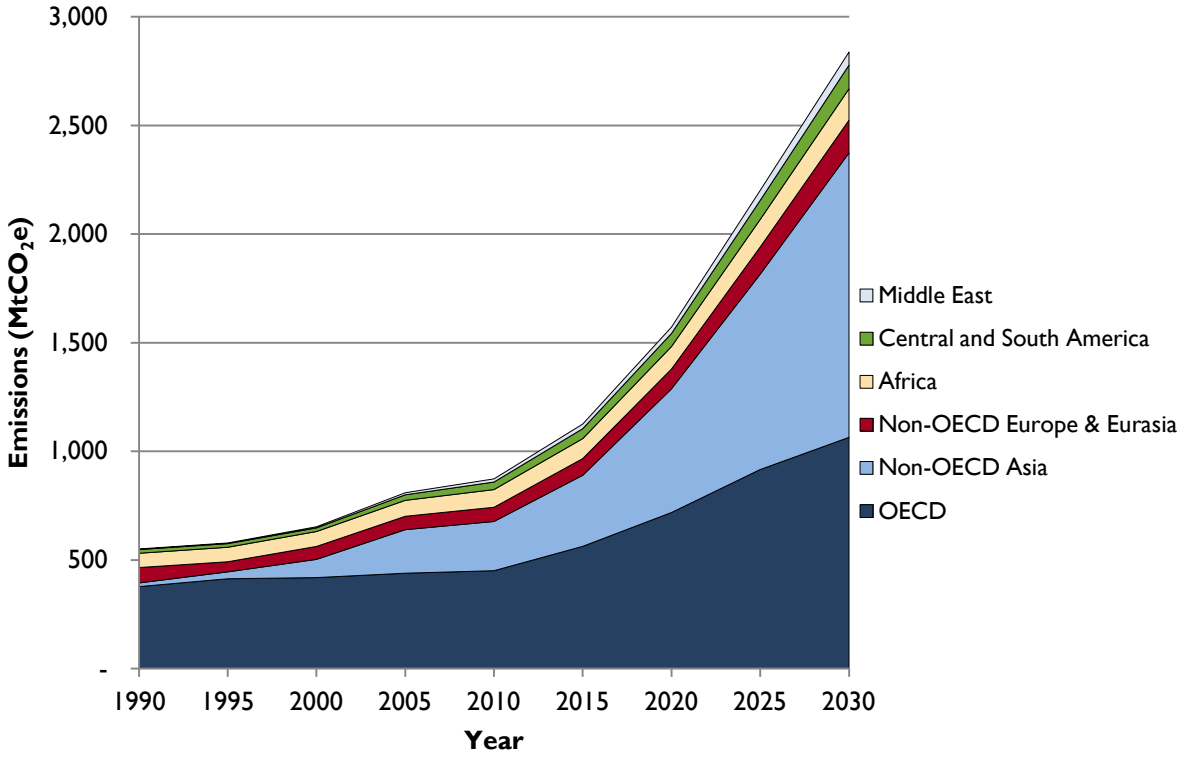


Table 4-1 lists the F-GHGs included in this analysis of the industrial sector with their atmospheric lifetime, global warming potentials (GWP), and associated uses or emission sources. Although the GWPs have been updated by the IPCC in the Third Assessment Report (TAR) and again in the Fourth Assessment Report (AR4), estimates of emissions in this report continue to use the GWPs from the Second Assessment Report (SAR) in order to be consistent with international reporting standards under the United Nations Framework Convention on Climate Change (UNFCCC). However, some of the F-GHGs estimated in this report did not have GWPs listed in the SAR. In these cases, this report uses the TAR GWPs.

Table 4-1: F-GHG Chemicals - Partial List

Chemical	Life-time (yrs)	GWP (100-yr)	Use
Hydrofluorocarbons (HFCs)			
HFC-23	264	11,700	Byproduct of HCFC-22 production, used in very low temperature refrigeration, blend component in fire suppression, and plasma etching and cleaning in semiconductor production.
HFC-32	5.6	650	Blend component of numerous refrigerants.
HFC-41	3.7	150	Not in commercial use today.
HFC-125	32.6	2,800	Blend component of numerous refrigerants and a fire suppressant.
HFC-134	10.6	1,000	Not in commercial use today.
HFC-134a	14.6	1,300	Most widely used HFC refrigerant, blend component of other refrigerants, propellant in metered-dose inhalers and aerosols, and foam blowing agent.
HFC-152a	1.5	140	Blend component of refrigerant blends, propellant in aerosols, foam blowing agent.
HFC-143	3.8	300	Not in commercial use today.
HFC-143a	48.3	3,800	Refrigerant blend component.
HFC-227ea	36.5	2,900	Fire suppressant, foam blowing agent, and propellant for metered-dose inhalers.
HFC-236ea	10.0[a]	1200[a]	Not in commercial use today.
HFC-236fa	209	6,300	Refrigerant and fire suppressant.
HFC-245ca	6.6	560	Not in commercial use today.
HFC-245fa	7.2[a]	950[a]	Foam blowing agent and under consideration as a refrigerant.
HFC-365mfc	9.9[a]	890[a]	Foam blowing agent.
HFC-43-10mee	17.1	1,300	Cleaning solvent.
Perfluorocarbons (PFCs)			
CF_4	50,000	6,500	Byproduct of primary aluminum production. Plasma etching and cleaning in semiconductor production and component of low temperature refrigerant blends.
C_2F_6	10,000	9,200	Byproduct of primary aluminum production. Plasma etching and cleaning in semiconductor production.
C_3F_8	2,600	7,000	Component of low-temperature refrigerant blends and fire suppressant. Used in plasma cleaning in semiconductor production.
C_4F_{10}	2,600	7,000	Fire suppressant.
c-C_4F_8	3,200	8,700	Not in much use, if at all, today. Emerging for plasma etching in semiconductor production.
C_5F_{12}	4,100	7,500	Not in much use, if at all, today.
C_6F_{14}	3,200	7,400	Precision cleaning solvent.
Nitrogen Trifluoride (NF_3)			
NF_3	740[b]	8,000[b]	Plasma cleaning in semiconductor production.
Sulfur Hexafluoride (SF_6)			
SF_6	3,200	23,900	Cover gas in magnesium production and casting, dielectric gas and

Chemical	Life-time (yrs)	GWP (100-yr)	Use
			insulator in electric power equipment, used to test fire suppression discharge in military systems and civilian aircraft, atmospheric and subterranean tracer gas, sound insulation, process flow-rate measurement, medical applications, and formerly an aerosol propellant. Used for plasma etching in semiconductor production.

Table excludes ozone-depleting substances controlled by the Montreal Protocol.
GWPs and atmospheric lives are reprinted from the Intergovernmental Panel on Climate Change, Second Assessment Report (IPCC, 1996), except as noted below.
[a] IPCC, 2001. Third Assessment Report.
[b] Molina, L.T., P.J. Woodbridge, and M. Molina, 1995.

4.1 Adipic Acid and Nitric Acid Production (N_2O)

4.1.1 Source Description

N_2O is emitted during the production of adipic and nitric acids, both of which are feedstocks or components to the manufacture of a variety of commercial products.

Adipic acid (hexane-1, 6-dioxic acid) is a white crystalline solid used as a feedstock in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Worldwide, the largest single use of adipic acid is carpet manufacturing, accounting for 30 percent of the market (Chemical Week, 2007). By treating nitrogen oxides (NOx) and other regulated pollutants in the waste gas stream, N_2O emissions can be reduced. Studies confirm that these abatement technologies can reduce N_2O emissions by more than 95 percent, depending on plant specifications (Riemer et al., 1999). Emissions calculations for this source use adipic acid production plant capacity and default emission factors to estimate growth.

Nitric acid (HNO_3) is an inorganic compound used primarily to make synthetic commercial fertilizer. It is also a major component in the production of adipic acid and explosives. During the catalytic oxidation of ammonia, N_2O is formed as a byproduct and released from reactor vents into the atmosphere. Calculations for this source use projected fertilizer use to estimate growth in nitric acid production. N_2O emissions estimates for adipic and nitric acid are combined in this chapter because country-reported data often combines these sources.

4.1.2 Source Results

Between 1990 and 2005, N_2O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 $MtCO_2e$ to 126 $MtCO_2e$ (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of global N_2O emissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.

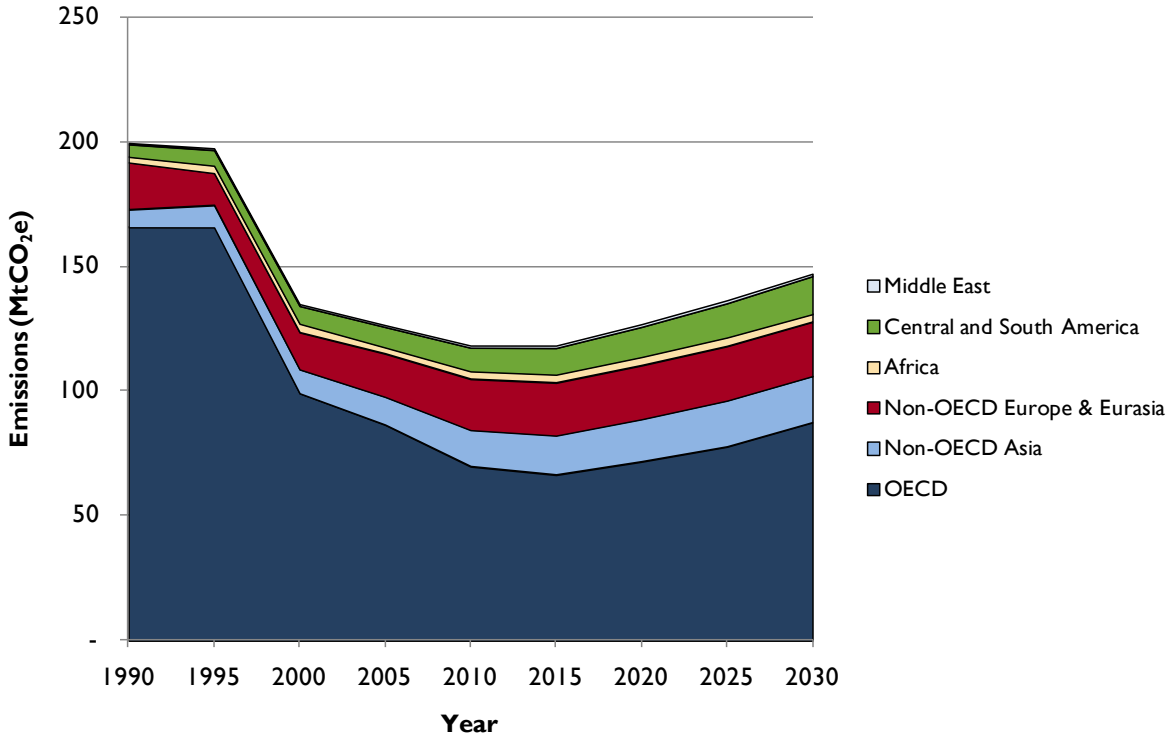
From 2005 to 2030, N_2O emissions from nitric and adipic acid production are projected to increase 16 percent. This projection assumes continued increase in production, but does not assume further mitigation. The regional shift of emissions away from the OECD is expected to continue. The

OECD is projected to account for 59 percent of N_2O emissions from this source in 2030, down from 68 percent in 2005.

Table 4-2: Total N_2O Emissions from Adipic Acid and Nitric Acid Production ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total N_2O	199.8	197.7	134.9	126.5	118.3	118.2	126.9	136.5	147.2

Exhibit 4-3: N_2O Emissions from Adipic Acid and Nitric Acid Production 1990 – 2030 ($MtCO_2e$)



The U.S., EU, and Canada began ramping up efforts to reduce N_2O emissions from adipic acid production in the late 1990s. Their effects can be seen in Exhibit 4-3 in the substantial reduction in emissions from 1995 to 2000. These control technologies can significantly reduce emissions, and their long-term effects may be even greater than illustrated in Exhibit 4-3 for countries with high technology penetration rates. Capacity expansions to meet increased global demand for adipic acid are expected in Asia, while market restructuring is expected to continue in Western Europe and North America (SRI, 2009; Chemical Week, 2007).

Fertilizer demand, and thus nitric acid use, is expected to continue to decline in Western Europe and increase elsewhere. The decline in several regions including Western Europe is due in part to concerns about nitrates in the water supply.

4.2 Use of Substitutes for Ozone Depleting Substances (HFCs)

4.2.1 Source Description

HFCs are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the Montreal Protocol. PFCs and hydrofluoroethers (HFEs) are also

used as alternatives, but to a substantially lesser extent than HFCs. Emissions from these gases are thus not estimated in this report. ODSs, which include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), have been used in a variety of industrial applications including refrigeration and air conditioning equipment, aerosols, solvent cleaning, fire extinguishing, foam production, and sterilization. Although the HFCs that would replace the ODSs are not harmful to the stratospheric ozone layer, they are powerful greenhouse gases.

Calculations of HFC emissions from the use of substitutes for ODSs are modeled by end use and country. End uses are expected to transition from ODSs to HFCs (and other substitutes) in response to the ODS phaseout required under the Montreal Protocol. For more information on the modeling approach, see section 7.2.2.

This section reports increases in emissions of HFCs used as substitutes for ODSs. However, the ODSs which HFCs are replacing are also greenhouse gases, in many cases more potent than the substitutes now being used. Thus, although emissions of HFCs used as substitutes of ODSs are increasing, the radiative forcing from the CFCs and HCFCs they replace would have been much higher had the phaseout of ODSs not taken place.[2]

4.2.2 Source Results

Table 4-3, Exhibit 4-4, and Exhibit 4-5 illustrate the rapid growth expected in the emissions for this source. In 1995, HFC emissions from ODS substitutes were only 63 $MtCO_2e$,[3] but by 2005, global emissions are estimated to have grown to 308 $MtCO_2e$. The growth in emissions up to 2005 is primarily driven by the transition to HFCs under the Montreal Protocol in OECD nations, which account for three quarters of 2005 emissions.

This trend is expected to accelerate in the early part of this century: from 2005 to 2030, emissions from this source are projected to increase rapidly, from 308 $MtCO_2e$ to 1,903 $MtCO_2e$, an increase of over 500 percent. The emissions contribution from non-OECD countries will play an increasingly important role. Although the OECD accounts for three quarters of HFC emissions from the use of ODS substitutes in 2005, by 2030 this share is expected to drop to less than half. This growth in non-OECD emissions is driven by both strong expected demand for refrigeration and air conditioning equipment (the largest source of HFC emissions) in developing countries and a transition to low- and no-GWP alternatives in OECD countries. Global emissions by end-use sector are provided in Exhibit 4-5.

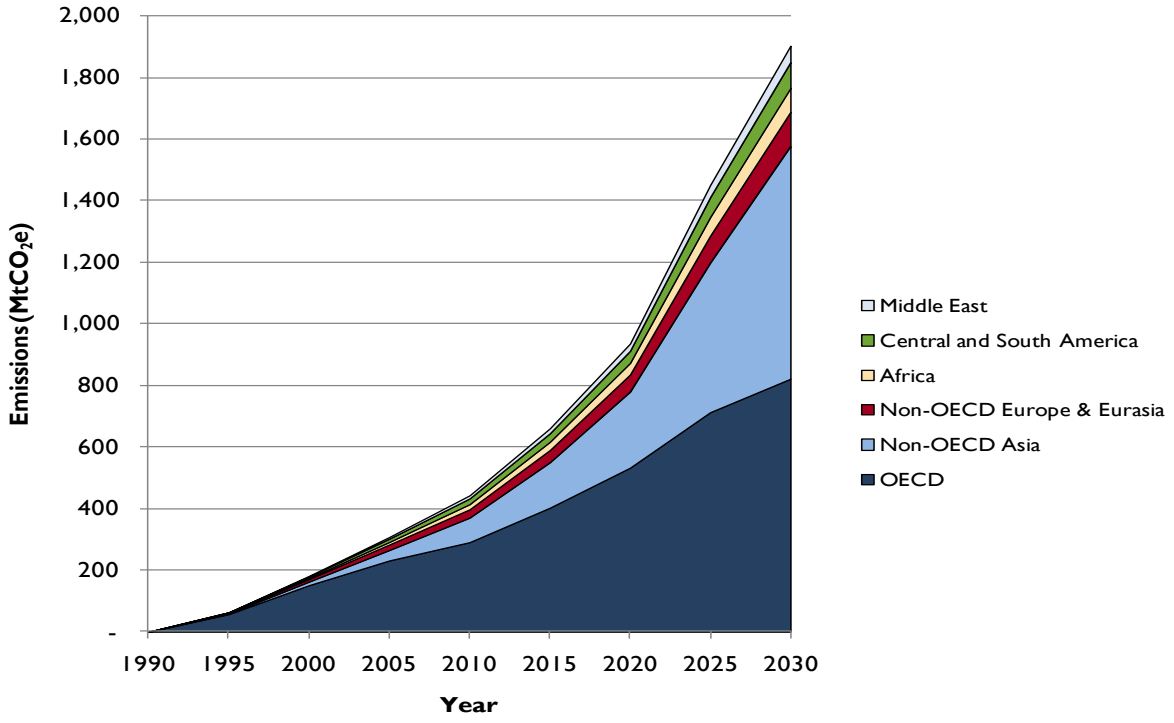
Table 4-3: Total HFC Emissions from Substitutes for Use of Ozone-Depleting Substances ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total HFCs	-	63.5	181.4	307.7	442.8	660.2	935.6	1,451.0	1,902.7

[2] For an estimate of the climate benefits of phasing out ODSs, see Velders et al. (2007).

[3] 1990 emissions for ODS substitutes were not estimated for all countries and are not presented here. In 1990, emissions for this category were negligible, with U.S. emissions accounting for less than 0.5 $MtCO_2e$.

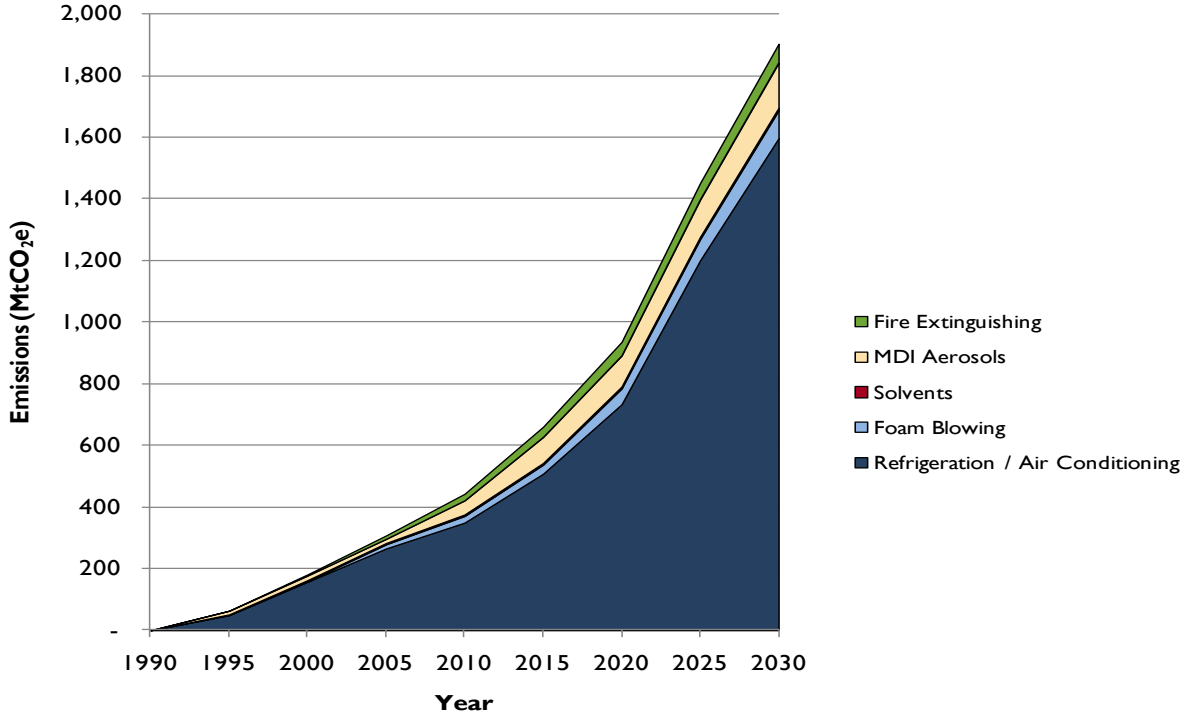
Exhibit 4-4: HFC Emissions from Use of Substitutes for Ozone-Depleting Substances 1990 – 2030 by Region ($MtCO_2e$)



The non-OECD Asia region illustrates this rapid growth: HFC emissions in this region are projected to grow from 34 $MtCO_2e$ in 2005 to 756 $MtCO_2e$ in 2030, an average annual growth rate of 88 percent. China, and to a lesser extent India, are the main sources of emissions in this region, and their rapid economic growth (a proxy for refrigeration and air conditioning demand) drives emissions growth in turn. Expected economic growth in these nations significantly exceeds expected growth in other developing countries.

HFC emissions in developed countries are expected to grow as well, although at a slower pace compared to developing countries. For example, HFC emissions from the OECD are expected to grow from 232 $MtCO_2e$ in 2005 to 822 $MtCO_2e$ in 2030, an average annual growth rate of 29 percent. In contrast to developing countries, this emissions growth in developed countries is driven primarily by the aging of existing equipment, as opposed to growth in the amount of equipment used. Emissions from refrigeration and air conditioning equipment occur throughout the equipment's lifetime (up to several decades), as refrigerant slowly leaks from the equipment or is emitted at service and disposal events. Enhanced recovery and reuse, transitions to more efficient equipment, and the use of low- or no-GWP alternatives could avert these projected emissions increases. Appendix F provides a detailed disaggregation of emissions from refrigeration and air conditioning end-use sector types by region.

Exhibit 4-5: HFC Emissions from Use of Substitutes for Ozone-Depleting Substances 1990 – 2030 by Sector ($MtCO_2e$)



4.3 HCFC-22 Production (HFCs)

4.3.1 Source Description

Trifluoromethane (HFC-23) is generated and emitted as a byproduct during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used primarily as a feedstock for production of synthetic polymers and, secondarily, in emissive applications (primarily air conditioning and refrigeration). Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out under the Montreal Protocol. However, feedstock production is permitted to continue indefinitely. Estimates in this section are associated with both types of HCFC-22 production.

HFC-23 emissions from HCFC-22 production can be avoided through thermal destruction and reduced through process optimization. Destruction of HFC-23 from this source in non-Annex I countries is a major source of credits in the CDM program. All producers in Annex I countries have implemented process optimization and/or thermal destruction to reduce HFC-23 emissions. In a few cases, HFC-23 is collected and used as a substitute for ozone-depleting substances, mainly in very-low temperature refrigeration and air conditioning systems. Emissions from this use are quantified under air conditioning and refrigeration and are therefore not included here. HFC-23 exhibits the highest global warming potential of the HFCs, 11,700 under a 100-year time horizon, with an atmospheric lifetime of 264 years.

4.3.2 Source Results

As shown in Table 4-4, global HFC-23 emissions from HCFC-22 production grew by 72 percent between 1990 and 2005, driven by 98 percent growth in global HCFC-22 production during that period. Emissions grew at a slower rate than production due to the implementation of thermal destruction and process optimization in Europe and the United States. Recent research such as Miller et al. (2010) uses atmospheric measurements to estimate total emissions of HFC-23, allowing comparison between top-down measurements and the bottom-up analysis presented in this report. While bottom-up emission estimates prior to 2006 fall within the uncertainty range of global estimates as published by Miller et al., atmospheric measurements for 2009 indicate that the projection methodology used in this report may not fully account for recent mitigation efforts.

Table 4-4: Total HFC-23 Emissions from HCFC-22 Production ($MtCO_2e$)

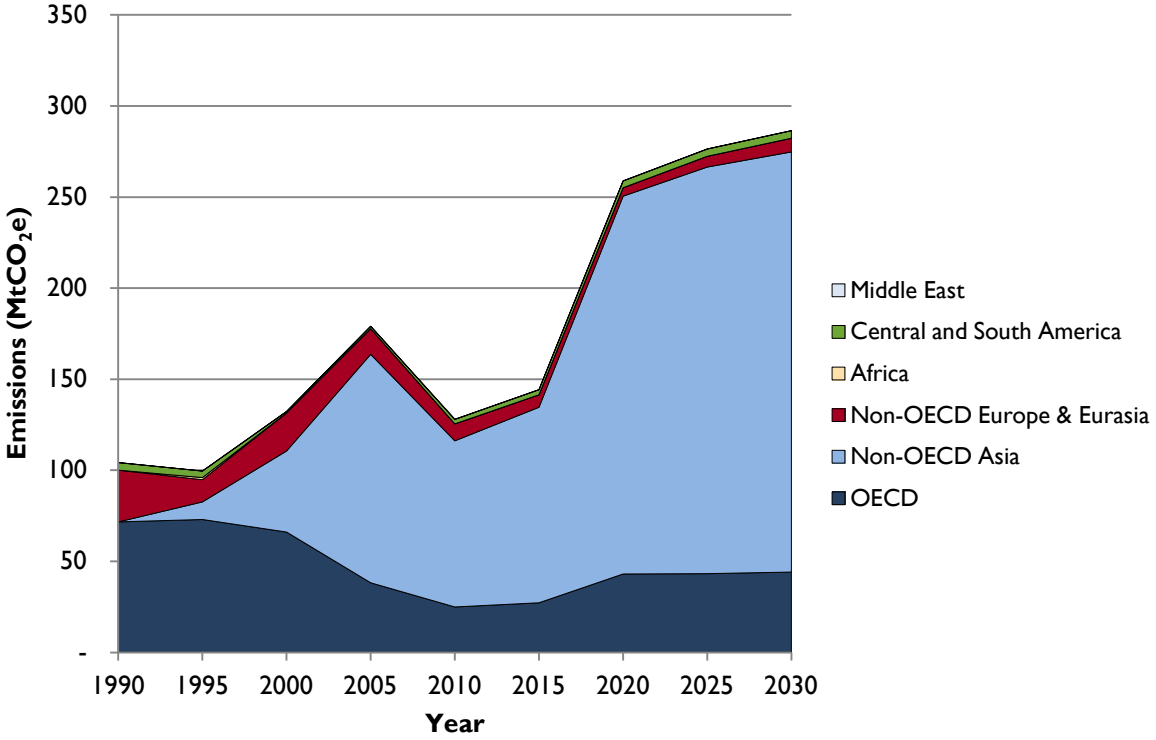
Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total HFC-23	104.2	99.5	132.2	179.0	127.9	144.2	258.8	276.3	286.4

Between 2005 and 2030, world HFC-23 emissions from HCFC-22 production are expected to increase by 60 percent. This projection includes a phaseout of non-feedstock HCFC-22 production in developed countries between 2015 and 2020, which results in a temporary reduction in HFC-23 emissions over that period. HCFC-22 production is expected to increase through 2030 because of feedstock uses.

Exhibit 4-6 reveals a striking shift of the majority of emissions from OECD countries to non-OECD Asia between 1990 and 2005. This is due to (1) a combination of increased use of emission controls and the phaseout of HCFC-22 under the Montreal Protocol in OECD countries and (2) increased HCFC-22 production in China and India. Thus, while HFC-23 emissions from OECD countries have declined by half, emissions from non-OECD Asia increased from a negligible level in 1990 to 70 percent of global HFC-23 emissions in 2005. Over the projection period, emissions are expected to grow in both regions, but will grow much more quickly in non-OECD Asia than in the OECD. Emissions from other regions are minor compared to these two regions. In 1990, the three largest emitters for this source were the U.S., Russia, and Japan, which together accounted for 75 percent of all emissions. In 2030, the three largest emitters are projected to be China, India, and Mexico. It is anticipated that these nations will account for 91 percent of all HFC-23 emissions from this source, while China alone is expected to be the world's major HFC-23 emitter, accounting for 51 percent of total emissions.

In the OECD, HFC-23 emissions decreased between 1990 and 2005 due to process optimization and thermal destruction. The U.S. and the European Union (EU) drove these trends. Although emissions increased in the EU between 1990 and 1995 due to increased production of HCFC-22, a combination of process optimization and thermal oxidation led to a sharp decline in EU emissions after 1995, resulting in a net decrease in emissions of 74 percent for this region between 1990 and 2005. U.S. emissions declined by 57 percent during the same period, despite a 12 percent increase in HCFC-22 production.

Exhibit 4-6: HFC-23 Emissions from HCFC-22 Production 1990 – 2030 ($MtCO_2e$)



As illustrated in Exhibit 4-6, HFC-23 emissions in developed countries are predicted to increase between 2005 and 2030 due to increasing production and use of HCFC-22 for feedstock purposes. Several factors mitigate the emissions increase: (1) Japan's implementation of either thermal abatement or HFC-23 capture (for use) for 100 percent of its production beginning in 2005 (JICOP, 2006); (2) 100 percent implementation of thermal abatement in all EU countries; (3) closure of the HCFC-22 production plants in Greece, France, Italy, and the U.K. between 2006 and 2008; and (4) the HCFC-22 production phaseout scheduled under the Montreal Protocol, which is occurring gradually between 2000, 2015, and 2020.

In non-OECD Asia, particularly in China, emissions have increased quickly due to a rapid increase in the production of HCFC-22 over the historical period. This production is meeting growing demand for unitary air conditioning, for commercial refrigeration, and for substitutes to chlorofluorocarbons currently being phased out in developing countries under the Montreal Protocol, as well as demand for HCFC-22 as a feedstock in the manufacture of polytetrafluoroethylene (PTFE) also known by its brand name Teflon (UNEP, 2003 and 2007). Emissions of HFC-23 from HCFC-22 production are expected to continue to increase in non-OECD Asia through 2030. Emissions increase through 2015, as HCFC-22 non-feedstock production is essentially unrestricted. After 2015, the emission growth slows as HCFC-22 non-feedstock production is restricted by the Montreal Protocol. Emissions begin growing at a faster rate around 2025 as HCFC-22 feedstock production outgrows non-feedstock production.

4.4 Electric Power Systems (SF_6)

4.4.1 Source Description

SF_6 is used as both an arc quenching and insulating medium in electrical transmission and distribution equipment. SF_6 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, SF_6 gas analysis, or disposal. The manufacture of equipment for electrical transmission and distribution can also result in SF_6 emissions, but this source is not included in this report.[4]

Several factors affect SF_6 emissions from electrical equipment, including the type and age of SF_6-containing equipment, and the handling and maintenance protocols used by electric utilities. Historically, approximately 20 percent of total global SF_6 sales have been attributed to electric power systems, where the SF_6 is believed to have been used primarily to replace emitted SF_6. Approximately 60 percent of global sales have gone to manufacturers of electrical equipment, where the SF_6 is believed to have been mostly banked in new equipment (Smythe, 2004).

Calculations of SF_6 emissions from this source use electricity usage projections as a proxy for the amount of electrical transmission and distribution equipment being used and the estimated emissions from that equipment. Voluntary programs encourage practices to reduce emissions of SF_6 from electrical equipment, but enhanced future mitigation from these programs are not explicitly included in the estimates.

4.4.2 Source Results

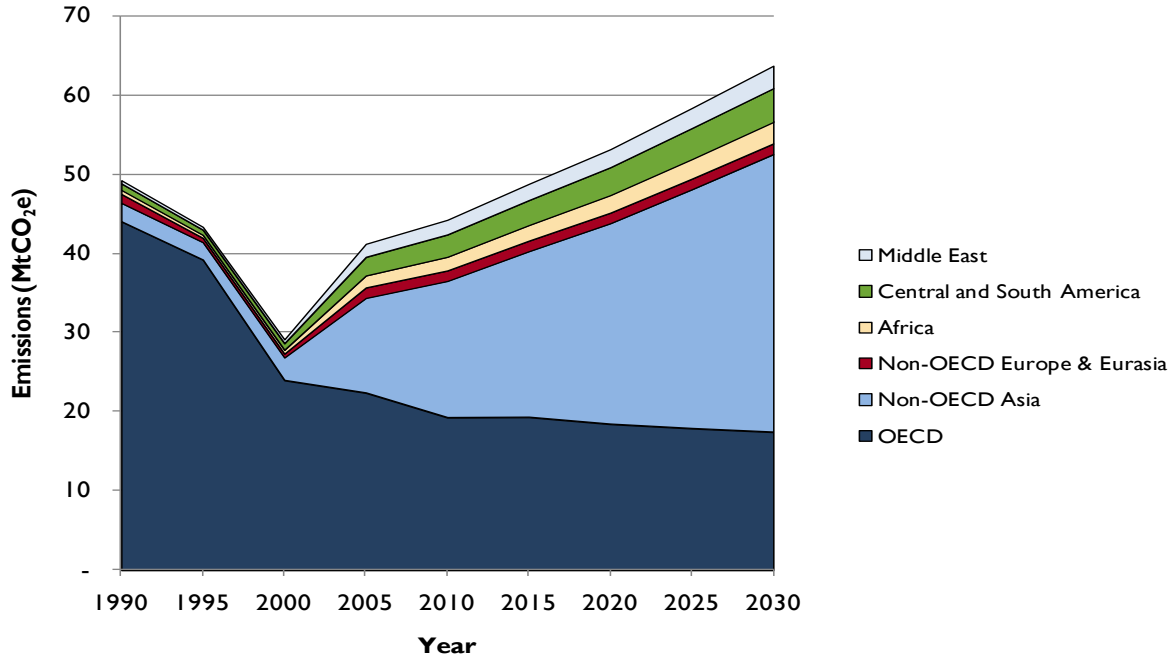
Global emissions from electric power systems are believed to have decreased 16 percent between 1990 and 2005, from 49 to 41 $MtCO_2e$ (see Table 4-5 and Exhibit 4-7). This emissions decline is based on declining SF_6 sales to utilities and estimated equipment retirements. The cost of SF_6 gas increased significantly in the mid-1990s, which motivated electric utilities to implement improved management practices to reduce their use of SF_6. However, sales of SF_6 increased by over 37 percent between 2000 and 2003, reversing the trend observed in the previous decade (Smythe, 2004). In addition, equipment retirements (based on a 40-year equipment lifetime) are estimated to have more than doubled between 2000 and 2003. Together, these two trends result in an increase in global emissions beginning in 2003. The global increase in SF_6 emissions is reflected in the trends of the individual regions except for the U.S., the EU, and Japan. Country-reported data for these three regions shows that SF_6 emissions from electric power systems declined from 1990 through 2003.

Table 4-5: Total SF_6 Emissions from Operation of Electric Power Systems ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total SF_6	49.3	43.4	29.1	41.2	44.2	48.8	53.2	58.4	63.8

[4] While these emissions were not explicitly estimated in this report, some 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.

Exhibit 4-7: SF_6 Emissions from Electric Power Systems 1990 – 2030 ($MtCO_2e$)



From 2005 to 2030, SF_6 emissions from electric power systems are projected to increase 55 percent, from41 to 64 $MtCO_2e$. This increase is driven by rapid projected electricity usage increases in non-OECD regions. In the U.S. and the EU, emissions are expected to continue to decline as utilities, through government-sponsored voluntary and mandatory programs, implement reduction measures such as leak detection and repair and gas recycling practices.

In contrast, emissions from non-OECD Asia, Africa, Central and South America, and the Middle East are expected to continue to increase over the projection period. In these countries, it is assumed that SF_6-containing equipment has been installed relatively recently, and that all equipment is new. Consequently, as infrastructure expands to meet the demands of growing populations and economies, emissions are estimated to grow at a rate proportional to country- or region-specific net electricity consumption (EIA, 2009).[5] By 2030, non-OECD regions are expected to account for 57 percent of total emissions, up from 32 percent in 2005 and 7 percent in 1990.

4.5 Primary Aluminum Production (PFCs)

4.5.1 Source Description

Emissions of the perfluorocarbons CF_4 and C_2F_6 are generated during brief process upset conditions in the aluminum smelting process. During the aluminum smelting process, when the alumina (Al_2O_3) in the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur. These voltage excursions are termed "anode effects" (AEs). Anode effects produce CF_4 and C_2F_6 emissions when carbon from the anode, instead of reacting with alumina, as it does during normal operating conditions, combines with fluorine from the dissociated molten cryolite bath combine. In general, the magnitude of emissions for a given level of production depends on the

[5] Electricity consumption growth rates are assumed to equal the growth rates in world total net electricity generation from central producers, as provided by EIA, 2009.

frequency and duration of these anode effects; the more frequent and long-lasting the anode effects, the greater the emissions.

Calculations of PFC emissions from this source are based on historical and expected levels of aluminum production and emission intensities from historical experience. Emission factors vary by aluminum production technology. Voluntary programs encourage practices to reduce the frequency and duration of anode effects and PFC emissions, but enhanced future mitigation from these programs is not included here. Effective emission factors (e.g., GWP-weighted emissions per production) data for PFC emissions calculations in this section were taken from International Aluminum Institute (IAI) survey results (IAI, 2011). The IAI estimate of global emissions used plant-by-plant data not incorporated in this report.

Five different electrolytic cell types are used to produce aluminum: Vertical Stud Soderberg (VSS), Horizontal Stud Soderberg (HSS), Side-Worked Prebake (SWPB), Center-Worked Prebake (CWPB), and Point Feed Prebake (PFPB), which is considered the most technologically-advanced process to produce aluminum. PFPB systems can be further improved through the implementation of management and work practices, as well as improved control software. Facilities using VSS, HSS, SWPB, and CWPB cells can reduce emissions by retrofitting smelters with emission-reducing technologies such as computer control systems and point feeding systems, by shifting production to PFPB technology, and by adopting management and work practices aimed at reducing PFC emissions. This analysis accounts for the historical reduction in the effective emission factors realized by the sector but does not assume that aluminum producers have conducted retrofits or will continue to introduce technologies and practices aimed at reducing PFC emissions.

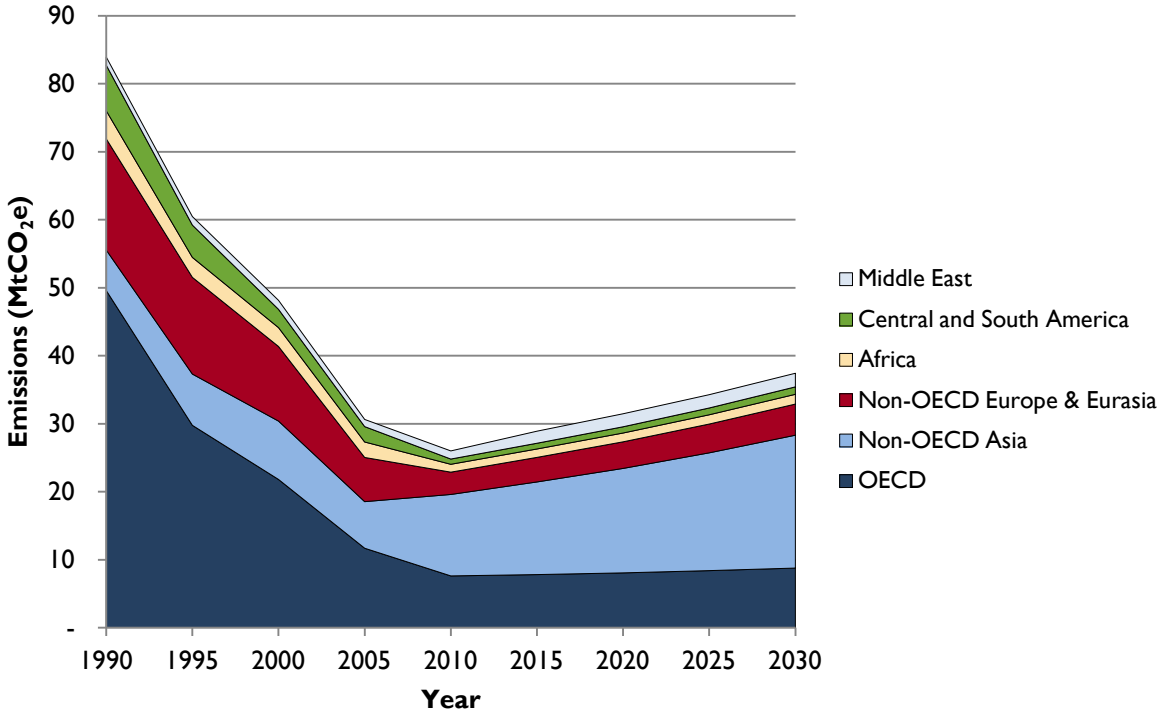
4.5.2 Source Results

Table 4-6 and Exhibit 4-8 present total PFC emissions from aluminum production under the analysis from 1990 to 2030. Between 1990 and 2005, global emissions declined from 84 to 31 $MtCO_2e$. This significant decline was the result of voluntary measures undertaken by global smelters to reduce their AE minutes per cell day. These measures included incremental improvements in smelter technologies and practices, and a shift in the share of SWPB-related production to more state-of-the-art PFPB facilities. Emission reductions were offset by a 65 percent increase in global aluminum production between 1990 and 2005. The IAI estimates of PFC emissions from aluminum manufacture are similar (e.g., within −5 to +8 percent depending on the year) to the estimates presented here, and may reflect more accurate information on the actual emissions from individual facilities using a particular electrolytic cell type.

Table 4-6: Total PFC Emissions from Primary Aluminum Production ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total PFCs	83.9	60.4	48.1	30.6	26.0	28.9	31.4	34.3	37.4

Exhibit 4-8: PFC Emissions from Primary Aluminum Production 1990–2030 ($MtCO_2e$)



From 2005 to 2030, emissions from this source are projected to grow about 22 percent, from 31 to 37 $MtCO_2e$. Over this time period, aluminum production is expected to grow at about 2.5 percent per year.

In 1990, OECD emissions from aluminum production accounted for 59 percent of global emissions from aluminum production; however, by 2005, this share has reduced to 38 percent. From 2005 to 2030, PFC emissions from aluminum production in the OECD are expected to decrease by 25 percent,and will account for 23 percent of global emissions from aluminum production. Aluminum production is expected to grow at about 2.5 percent per year with a shift in major production to developing countries including China. In 2030, China is projected to account for 22 percent of global production, compared to 3 percent in 1990 and 7 percent in 2000.

In 2030, non-OECD Asia is projected to account for 52 percent of global emissions from aluminum production, compared to 7 percent in 1990 and 22 percent in 2005. In 2030, non-OECD Europe and Eurasia are projected to account for 12 percent of global emissions from aluminum production, compared to 19 percent in 1990 and 21 percent in 2005.

The trends in aluminum production and resulting PFC emissions in the EU and the United States generally follow the OECD trend. Historical U.S. emissions (1990 to 2005) reflect AE reductions already realized by members of EPA's Voluntary Aluminum Industrial Partnership (VAIP) as well as a general decline (38.7 percent) in aluminum production. However, under this analysis, future U.S. emissions (from 2005 forward) are projected to increase in 2010 and remain relatively flat through 2030 (based on National Communications to the UNFCCC).

In general, the declining global emission levels through 2005 reflect the successful reduction in the frequency and duration of anode effects. From 2010 to 2030, the analysis assumes that the effective

emission factors (e.g., GWP-weighted emissions per production) will remain constant at 2010 values; consequently, emissions will be driven by increasing aluminum production.

4.6 Magnesium Manufacturing (SF_6)

4.6.1 Source Description

The magnesium metal production and casting industry uses SF_6 as a cover gas to prevent the spontaneous combustion of molten magnesium in the presence of air. Fugitive SF_6 emissions occur primarily during three magnesium manufacturing processes: primary production, die-casting, and recycling-based production. Additional processes that may use SF_6 include sand and gravity casting; however, these are believed to be minor sources and are not included in this analysis.

Emissions calculations in this section use magnesium production statistics and default emission factors. Although recent studies indicate some destruction of SF_6 in its use as a cover gas (Bartos et al., 2003), this analysis follows current IPCC guidelines (IPCC, 2006), which assumes that all SF_6 used is emitted to the atmosphere.

4.6.2 Source Results

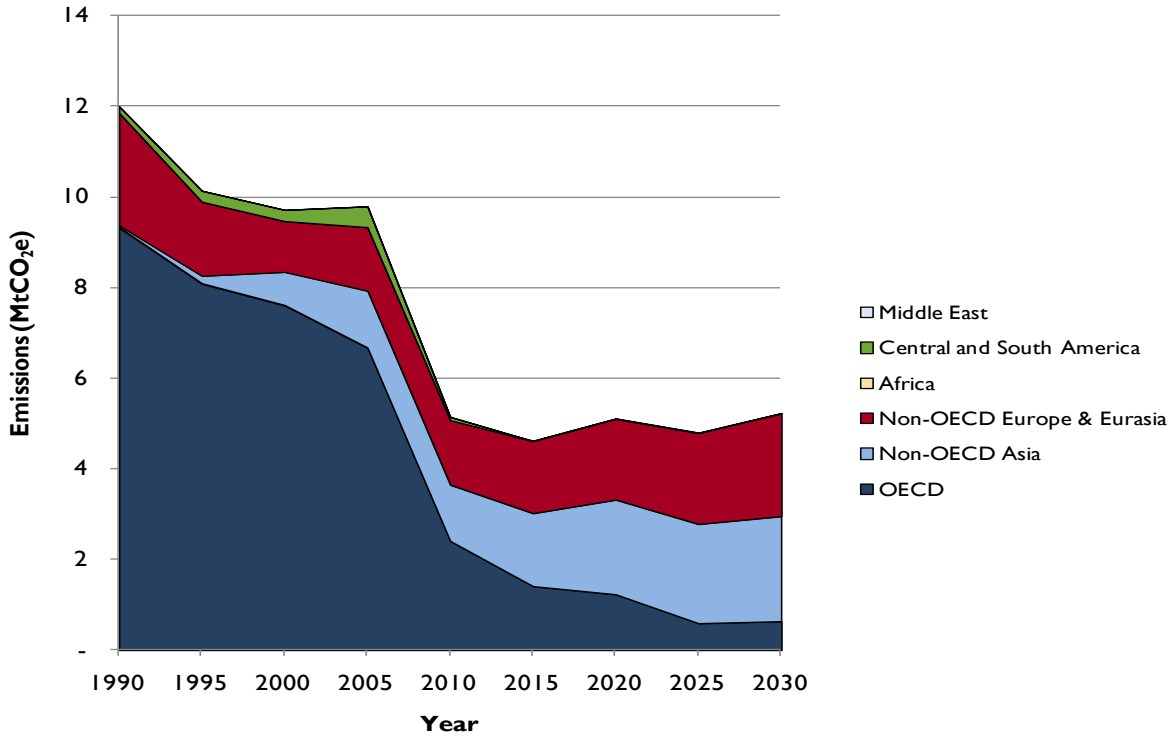
Between 1990 and 2005, SF_6 emissions from magnesium manufacturing have decreased 18 percent, from 12 to 10 $MtCO_2e$. Over this time period, magnesium production has increased, but this growth has been offset by major initiatives to phase-out the use of SF_6 in magnesium production in numerous countries. Total SF_6 emissions from magnesium manufacturing are displayed in Table 4-7 and Exhibit 4-9.

From 2005 to 2030, emissions from this source are projected to decrease further from 10 to 5 $MtCO_2e$, a decrease of about 47 percent. Emissions from OECD countries decrease significantly in the short term because of facility closures in North America and SF_6 phase-out efforts (USGS, 2010). As a result, the OECD share of global SF_6 emissions from magnesium manufacturing is projected to decrease from 68 percent in 2005 to 12 percent in 2030. Major SF_6 phase-out efforts are driven by the EPA's voluntary partnership in the United States and regulatory directives in Japan and Europe.

Table 4-7: Total SF_6 Emissions from Magnesium Manufacturing ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total SF_6	12.0	10.1	9.7	9.8	5.1	4.6	5.1	4.8	5.2

Exhibit 4-9: SF_6 Emission from Magnesium Manufacturing 1990 – 2030 ($MtCO_2e$)



SF_6 emissions from magnesium manufacturing in non-OECD Asia are projected to increase significantly from 2005 to 2030, increasing the region's global share of emissions from 13 percent to 44 percent. Emissions in the non-OECD Europe and Eurasia region experience similar growth. The overall increase in non-OECD Asia's share of global emissions is from an increase in Chinese primary magnesium production and die-casting fueled by local and foreign investment. China's emissions growth is driven by their die-casting operations (USGS, 2009) and by 10 percent of their primary production that is assumed to use SF_6 as the cover gas mechanism. Emissions from Central and South America are driven by production in Brazil. Brazil's emissions were estimated to have declined considerably since the implementation of CDM projects after 2005 involving a switch to SO_2 as a cover gas (UNFCCC, 2010a).

4.7 Semiconductor Manufacturing (HFCs, PFCs, SF_6, NF_3)

4.7.1 Source Description

The semiconductor industry currently uses several fluorinated compounds (CF_4, C_2F_6, C_3F_8, C_4F_8, C_4F_8O, HFC-23, NF_3, and SF_6) and N_2O during the fabrication process.[6,7] When used in the process, a fraction of gas that is not utilized may be released from the manufacturing equipment. The amount released depends upon the efficiency of the process, the integrity of the equipment, and the presence (or absence) of an abatement system. Although there are several applications where these gases are employed, nearly all are used in one of two processes: (1) the plasma etching of thin films, a

[6] The chemical compound CHF_3 is more commonly referred to as HFC-23; thus, the latter term is used here.
[7] N_2O and NF_3 were not considered in this analysis as they are not in the basket of gases for which emissions are reported to the UNFCCC.

manufacturing step, and (2) the cleaning of chemical-vapor-deposition (CVD) chambers, a preventative maintenance step. By-product emissions of CF_4 also result when a fraction of the heavier consumed gases is converted during the manufacturing process. Fluorinated greenhouse gases (F-GHGs) and N_2O are also used as heat transfer fluids. Total PFC, HFC, and SF_6 emissions from this source vary by process and device type.

Emission calculations for this source were developed using semiconductor production capacity statistics, capacity utilization assumptions, and default emission factors. PFC, HFC, and SF_6 emissions from this source can be reduced using chemical substitution, process optimization, and equipment to destroy these compounds in waste gas streams. Voluntary programs encourage adoption of these mitigation technologies. These projections assume reductions that have resulted or are anticipated to result from international voluntary climate commitments.

4.7.2 Source Results

Table 4-8 and Exhibit 4-10 show the emission estimates for the semiconductor manufacturing industry.

Between 1990 and 2005, total F-GHG emissions from the semiconductor manufacturing industry have increased 102 percent, from 13 to 26 $MtCO_2e$. This increase in emissions reflects underlying growth in semiconductor production partially offset by mitigation efforts.

In April 1999, the semiconductor manufacturing industry set an aggressive target to reduce PFC emissions. The World Semiconductor Council (WSC) then agreed to reduce PFC emissions to 10 percent below 1995 levels by the year 2010. WSC members include the industry organizations for the European countries, China[8], Japan, Korea, and the U.S. Since WSC members account for production of over 90 percent of the world's semiconductors[9], the goal is expected to have dramatic effects in decreasing emissions from semiconductor manufacturing over time.[10] The has set a post-2010 emission rate target as opposed to an absolute reduction. However given that this target was recently set it was not considered when this analysis was completed. .

Table 4-8: Total F-GHG Emissions from Semiconductor Manufacturing ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total PFCs	9.0	9.5	18.0	14.0	10.4	11.8	11.4	11.7	12.2
Total HFCs	0.8	0.7	0.8	0.7	0.9	1.0	1.1	1.1	1.1
Total SF_6	2.8	3.4	5.9	5.4	2.8	3.4	3.0	3.1	3.3
Total NF_3	0.1	0.1	3.1	5.	4.1	4.4	4.6	4.8	5.0
Total F-GHGs	**12.7**	**13.8**	**27.8**	**25.6**	**18.2**	**20.6**	**20.0**	**20.7**	**21.5**

[8] Although China joined the WSC in 2006, it has not yet committed to a reduction goal.
[9] According to the EPA's website on PFC Reduction/Climate Partnership for the Semiconductor Industry: http://www.epa.gov/semiconductor-pfc/international.html.
[10] The WSC goal takes into account NF3 emissions. Therefore for this analysis the "NF3 portion" of the WSC target was removed. The portion was estimated based on historical F-GHG emission estimates reported to EPA through the Voluntary Partnership with the semiconductor manufacturing industry: http://www.epa.gov/semiconductor-pfc/

Exhibit 4-10: F-GHG Emissions from Semiconductors Manufacturing 1990 – 2030 ($MtCO_2e$)

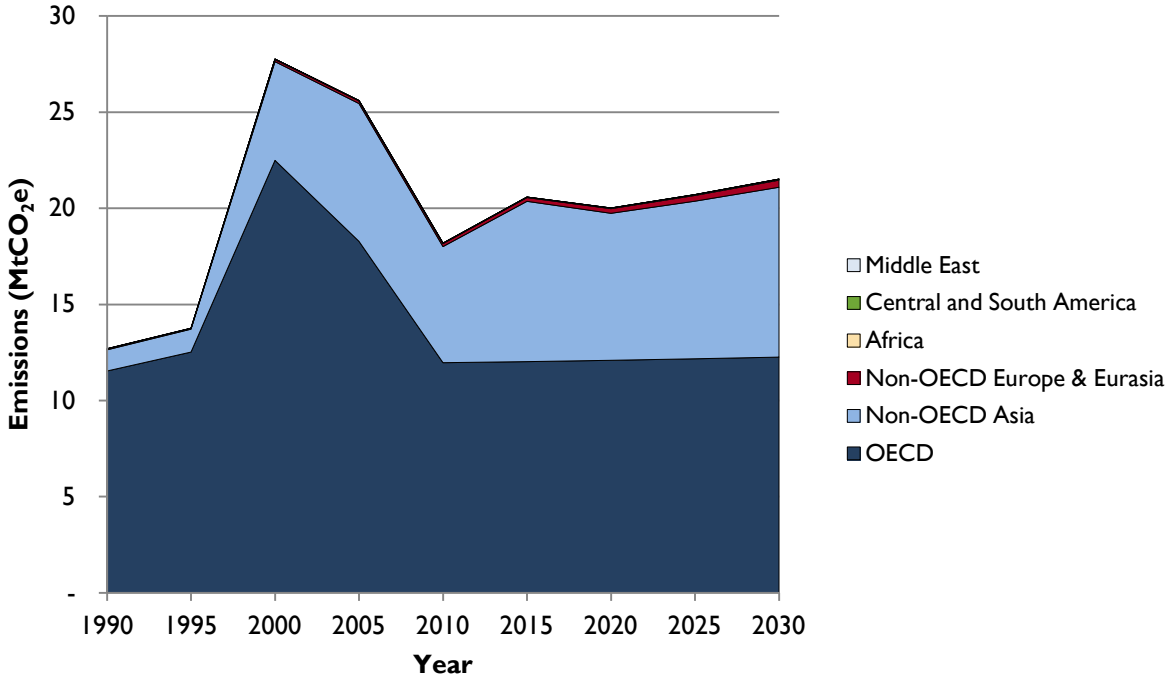


Exhibit 4-10 shows the annual emissions from the semiconductor manufacturing industry by region. The OECD and non-OECD Asia regions account for the vast majority of production, and therefore emissions. The highest-emitting countries worldwide in 2005 were Japan, the U.S., China, South Korea, and Russia.

Emissions from this source are projected to decrease by 16 percent from 2005 to 2030 from 26 $MtCO_2e$ to 22 $MtCO_2e$. Between 2005 and 2010, emissions are expected to decline as the semiconductor industry achieves its voluntary reduction targets. From 2010 to 2030, emissions are projected to grow by 18 percent, with an annual growth rate of less than 1 percent. This estimated low growth rate is based on the assumption that the WSC reduction goal will be maintained in future years.[11] Emissions from three out of the four countries that emitted the majority of PFCs in 2010 are predicted to experience zero growth. These countries include the U.S., Japan, and South Korea. The PFC emissions released by the fourth country, China, are predicted to increase by 15 percent from 2010 to 2020, but are then expected to have zero growth through 2030 due to the emissions goal that is expected to be set at a baseline of 10 percent of 2020 emissions (Bartos et al, 2008). The highest growth in emissions is projected for Singapore, where growth is expected to be over 18 percent for each of the four, five year periods from 2010 to 2030. Despite this growth, Singapore's emissions in 2030 will only account for 13 percent of global F-GHG emissions from semiconductor manufacturing.

[11] These assumptions are based on the WSC Joint Statement (WSC, 2010) which indicated that the WSC is on track to meet their reduction goals, and information from the International Technology Roadmap for Semiconductors (ITRS, 2009, Table ESH3a or b) which indicates that the WSC goal will be maintained through 2024. The goal was then carried through 2030.

4.8 Flat Panel Display Manufacturing (PFCs, SF_6, NF_3)

4.8.1 Source Description

Flat panel display (FPD) manufacturing uses SF_6, PFCs including CF_4, and NF_3, in the etching and chamber cleaning processes.[12] These F-GHGs are used for chemical vapor deposition (CVD) cleaning processes and plasma dry etching during manufacture of arrays of thin-film transistors on glass substrates, which switch pixels of liquid crystal displays and organic light emitting diode displays.

In order to reduce emissions, this sector may employ abatement technologies, including fueled combustion, plasma and catalytic technologies explicitly intended for F-GHG abatement. FPD manufacturing is a new source category in this report. Emissions calculations for this source use data on flat panel manufacturing capacity and industry growth trends. The projections for this sector assume continued rapid growth in a currently fast-growing industry, due to continued demand for and evolving generations of electronics products (e.g., televisions and computer monitors). Additionally the growth is predicated on the fact there will be increased demand for these newer technologies, particularly in developing nations such as China.

4.8.2 Source Results

Flat panel display manufacturing is a relatively new industry sector. By 2005, industry emissions have grown to about 3.9 $MtCO_2e$. Underlying this growth, flat panel displays have grown to over half of the electronic display market. In 2005, the OECD and non-OECD Asia regions accounted for 54 percent and 46 percent of F-GHG emissions from flat panel display manufacturing, respectively. The total emissions from the manufacture of FPDs are displayed in Table 4-9 below. China[13], Japan, Singapore, and South Korea contributed significantly to FPD manufacturing emissions.

From 2005 to 2030, emissions from this source are expected to grow by a factor of forty, to 162 $MtCO_2e$ in 2030. Between 2005 and 2010, FPD manufacturing capacity grew by a factor of 9, or an annual growth rate of more than 50 percent. This projection assumes large growth in the FPD industry, tapering from an assumed annual growth rate about 30 percent in 2010 to about 15 percent in 2030.[14] The OECD and non-OECD Asia are expected to remain dominant in the industry, while Africa, Central and South America, and non-OECD Europe and Eurasia do not contribute significantly to emissions from FPD manufacturing.

The OECD's emissions have continued to grow in absolute terms; however global totals have increased at a faster rate, resulting in the OECD emitting approximately 1 percent of the global FPD emissions in 2030. This is in part due to the assumed use of abatement technologies in some OECD countries, and because of a large increase in FPD manufacturing in China by 2030. The contribution of emissions by China, as a percent of world emissions from FPD manufacturing, increased from 18

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[12] NF_3 was not considered in this analysis as they are not included in the gases for which emissions are reported to the UNFCCC.

[13] 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 Taiwan is a member of the WLICC.

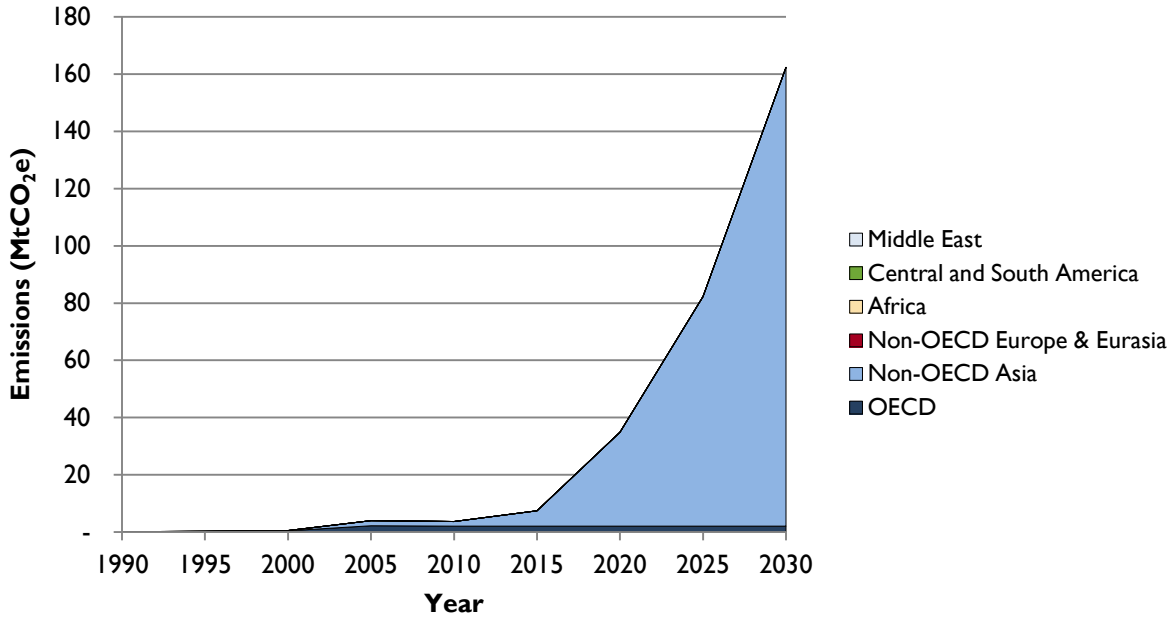
14 The annual growth rate of 15-30% assumed for the flat panel display industry is lower than the recent growth rate for the industry, but much higher than overall economic growth. For this reason, the emissions estimates for this industry can be thought of an upper bound for emissions from a fast-growing industry. If the industry grows much slower than it has in the past, then emissions would be lower.

percent in 2000 to 45 percent in 2005, and by 2010 China's emissions were 1.6 $MtCO_2e$, accounting for 44 percent of global emissions from FPD manufacturing.

Table 4-9: Total SF_6 and PFC Emissions from Flat Panel Display Manufacturing ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total PFCs	0.0	0.0	0.0	0.1	0.7	0.8	1.6	2.9	5.2
Total SF_6	0.1	0.2	0.4	3.3	0.5	3.7	26.6	66.2	133.2
Total NF_3	0.0	0.0	0.1	0.5	2.4	2.9	6.7	13.1	23.9
Total F-GHGs	**0.1**	**0.2**	**0.5**	**3.9**	**3.6**	**7.4**	**34.8**	**82.2**	**162.3**

Exhibit 4-11: SF_6, PFC, and NF_3 Emissions from Flat Panel Display Manufacturing 1990 – 2030 ($MtCO_2e$)



The share of global emissions from China is projected to drastically increase to 98 percent by 2030, increasing to 158.5 $MtCO_2e$. This increase is a result of two key drivers. First, there is an expected increase in China's domestic demand for FPDs, and much of this demand will be met through domestic production (DisplaySearch, 2010). Second, in the later years of this analysis, China's share of world emissions is projected to steeply increase partly because other countries with large FPD manufacturing capacities are expected to meet and maintain a voluntary emissions reductions goal set by the World LCD Industry Cooperation Committee (WLICC). The WLICC is comprised of three member associations representing Taiwan,[15] Japan, and South Korea. The WLICC goal, which was agreed to by all three member associations, is to meet and maintain an aggregate 2010 F-GHG emission target of 10 percent of the projected business-as-usual 2010 emissions, or 0.8 MMTCE (3.0 $MtCO_2e$).[16] The WLICC member associations are estimated to have 96 percent of the world's FPD

[15] See footnote 13.

[16] The WLICC goal takes into account NF3 emissions. Therefore for this analysis the "NF3 portion" of the WLICC target was removed. The portion was estimated based on historical F-GHG emission estimates available to EPA through working with the WLICC to assess and analyze the data reported by the three country industry associations.

manufacturing capacity in 2010. By 2030 WLICC countries are still expected to maintain 82 percent of world FPD manufacturing capacity. In contrast in 2010, the WLICC countries are expected to emit only 79 percent of world F-GHG emissions from FPD manufacturing, and 2 percent in 2030. This low share of emissions versus capacity for the WLICC in 2030 is a direct result of the voluntary WLICC emission reduction goal and increasing FPD manufacturing capacity in China to meet domestic and global demand. In addition, in part because of the WLICC goal, the OECD and SE Asian countries' emissions are projected to remain steady and slightly increase, respectively, from 2015 to 2030.

4.9 Photovoltaic Manufacturing (PFCs, NF_3)

4.9.1 Source Description

Photovoltaic (PV) manufacturing causes emissions of PFCs, including CF_4 and C_2F_6, as well as NF_3, from etching and chamber cleaning processes used during the manufacture of PV cells.[17] Photovoltaic (PV) manufacturing is a new source category in this report.

Emissions depend on the particular substrate and process used in the production of PV cells. Substrates used in the industry include crystalline silicon, amorphous silicon, and other thin-films. CF_4 and C_2F_6 are used during manufacture of crystalline silicon (c-Si) PV cells; NF_3 is used during manufacture of amorphous silicon (a-Si) and tandem a-Si/nanocrystaline (nc) silicon PV cells. Etching and cleaning processes for PV cells manufactured on other thin films do not utilize GHGs. Calculations in this section utilize statistics on PV production capacity which take into account projected increases in renewable energy use.

4.9.2 Source Results

Historically, PV manufacturing has not resulted in significant GHG emissions. For 1990 and 1995, PV manufacturing, and as a result emissions, were assumed to be negligible. In the base year 2005, PFC emissions are estimated to have been about 0.5 $MtCO_2e$, based on PV production capacity of about 2,200 MW or 13.8 million meters squared of substrate.

The trends for the PV manufacturing industry used for this report were based on the assumption that demand for, and therefore production of PV cells rapidly increases through 2030. This projection assumes rates of growth in this sector will remain high due to the increasing demand for electric power, efforts to reduce dependence on fossil fuels, and a growing understanding of the environmental effects of traditional sources of energy. The estimates developed for this report do not explicitly take into account any current or future policies (renewable energy standards), as it is uncertain at this point how to quantify the effect on demand for PV cells.

PFC emissions from PV manufacturing are estimated to grow quickly between 2005 and 2030, from 0.5 to 128 $MtCO_2e$. This projection assumes very large growth in solar energy usage to about 200 GW installed PV capacity in 2030, from 13 GW global installed PV capacity in 2008. Although this assumption is very large, the PV industry is growing quickly and one purpose of this projection is to

[17] Note that while the term PFC (strictly referring to only perfluorocarbon compounds) does not include all of the fluorinated compounds emitted from this source, specifically NF_3, the electronics manufacturing industry commonly refers to the mix of fluorinated compounds as PFCs. Therefore NF_3 emissions are included in this analysis.

understand the possible emissions that would result should that growth occur.[18] Total PFC emissions for the world from PV manufacturing are projected to grow by over 130 percent for each of the 5 year periods starting in 2000 through 2030. The emissions from the PV manufacturing industry for in 5-year increments from 1990 through 2030 are shown below in Table 4-10.

The OECD and non-OECD Asia country groups are projected to account for nearly all emissions from this source from 2005 through 2030 (see Exhibit 4-12). In 2005, the OECD countries contributed 76 percent of total PFC emissions from PV manufacturing. In 2010, China is expected to become the largest contributor of PV manufacturing emissions, accounting for 47 percent of world's PFC emissions, while the OECD's share of PFC emissions from PV manufacturing decreases to 43 percent of global emissions. Overall, the non-OECD Asia region contributes 57 percent of PFC emissions in 2010 from the manufacture of PVs. Other than the OECD and non-OCED Asia regions, the only other regions that manufacture PVs are the Middle East and non-OECD Europe and Eurasia, which combined contribute less than 1 percent of global PFC emissions from PV manufacturing through 2030. By the year 2030, EPA projected that China will be the highest contributor of PFC emissions from PV manufacturing, emitting an estimated 56.4MtCO_2e, with Japan, Germany, and Malaysia emitting 15.3, 13.0, and 10.3 MtCO_2e, respectively.

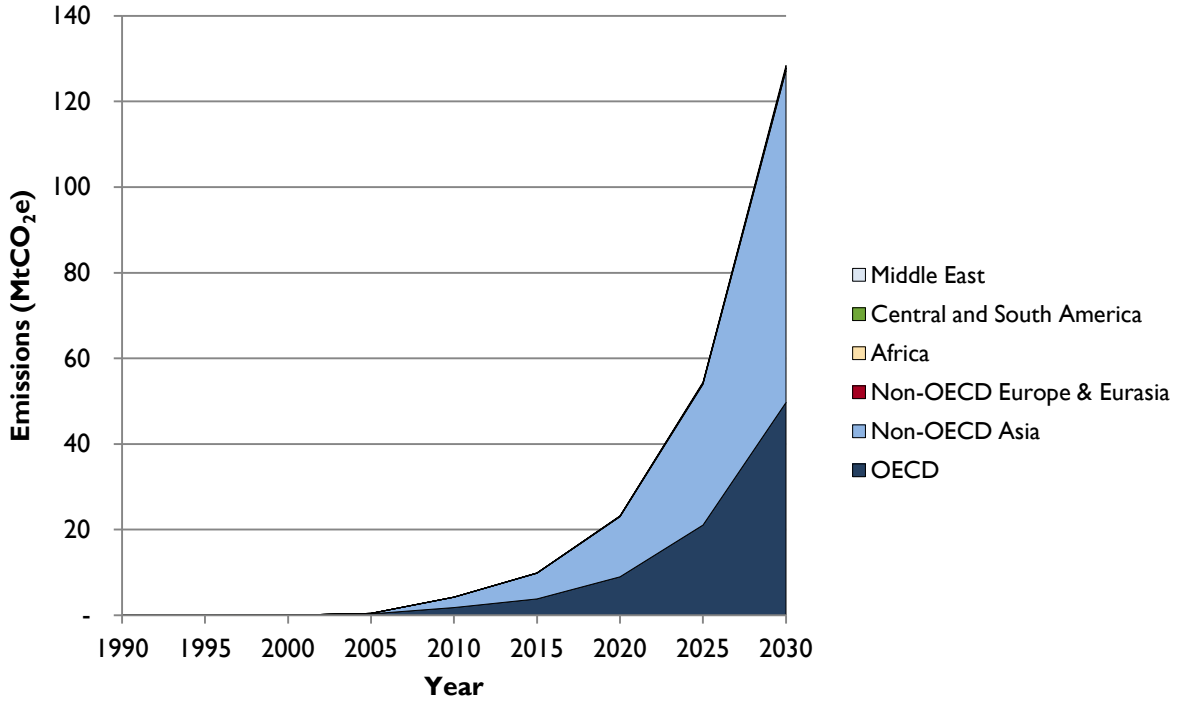
Table 4-10: Total PFC and NF_3 Emissions from Photovoltaic Manufacturing (MtCO_2e)[19]

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total PFC	-	-	0.0	0.5	3.9	8.5	18.9	46.0	112.1
Total NF_3	-	-	0.0	0.0	0.4	1.4	4.4	8.5	16.3
Total F-GHGs	**-**	**-**	**0.0**	**0.5**	**4.3**	**9.9**	**23.3**	**54.5**	**128.4**

[18] The projection assumes an annual industry growth rate approximately 19%. This growth rate is lower than the PV industry has achieved in some recent years, but much higher than total economic growth. For this reason, the emissions estimates in this section can be thought of as an upper bound for possible future emissions from a currently fast-growing industry. If the PV industry grows much more slowly than it has in the past, then emissions, then emissions would be lower.

[19] EPA readily had information available to estimate NF3 emissions for thus source category. Therefore they are provided here, despite the fact that NF3 emissions are not reported to the UNFCCC.

Exhibit 4-12: PFC and NF_3 Emissions from Photovoltaic Manufacturing 1990-2030 ($MtCO_2e$)



The significant global increase in PFC emissions from PV manufacturing is due to an expected increase in demand for clean, renewable energy, which equates to a large growth in PV manufacturing capacity. This demand is a result of future national GHG reduction regulations, increasing costs and risks of securing traditional energy supplies, the increasing need for energy in industrialized nations with growing populations, and a growing understanding of the environmental effects of traditional sources of energy. While PFC abatement was not explicitly considered in this analysis due to limited information, it may provide a potential option to reduce the estimated large future increases in PFC emissions from PV manufacturing.

4.10 Other Industrial Processes Sources (CH_4, N_2O)

4.10.1 Source Description

This source category includes emissions from the industrial processes sector that are relatively small and are thus grouped together. The data presented here include the following sources of CH_4 and N_2O:

- 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)

4.10.2 Source Results

The results for this source are presented in Table 4-11. Africa is the main contributor to emissions from this category, accounting for an average of 69 percent of emissions from 1990 to 2030. The OECD is the other major contributor for other industrial sources, accounting for an average of 26 percent of emissions from 1990 to 2030. The data in Table 4-11, below, are not fully comparable to data in the remainder of this report since emissions are not calculated for all countries.

Table 4-11: Total CH_4 and N_2O Emissions from Other Industrial Processes Sources ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	7.7	6.8	7.5	7.5	6.3	6.3	6.3	6.3	6.3
N_2O	80.8	82.8	81.3	77.0	76.3	76.3	76.3	76.3	76.3
Total	**88.5**	**89.6**	**88.9**	**84.5**	**82.6**	**82.6**	**82.6**	**82.6**	**82.6**

Exhibit 4-13 and Exhibit 4-14 illustrate trends in CH_4 and N_2O emissions for this source category.

Exhibit 4-13: CH_4 Emissions from Other Industrial Processes Sources 1990 – 2030 ($MtCO_2e$)

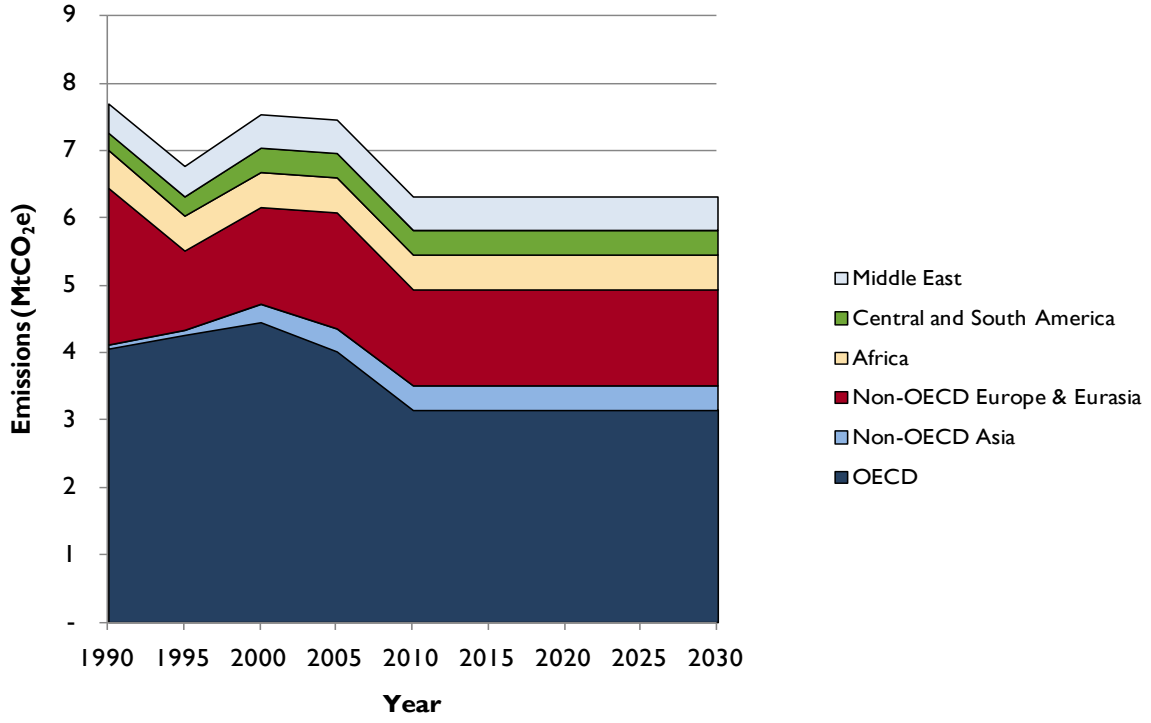
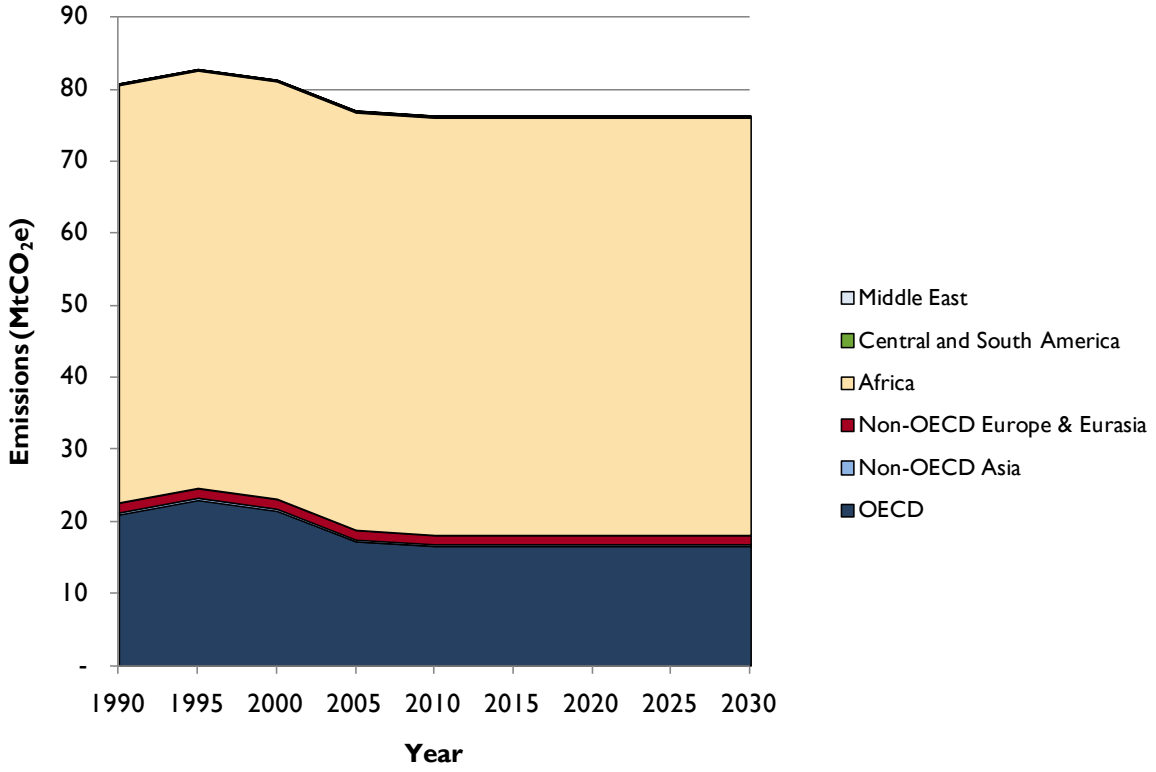


Exhibit 4-14: N_2O Emissions from Other Industrial Processes Sources 1990 – 2030 ($MtCO_2e$)



5 Agriculture

This section presents global CH_4 and N_2O emissions for 1990 to 2030 for the following agricultural sources:

- Agricultural Soils (N_2O)
- Enteric Fermentation (CH_4)
- Rice Cultivation (CH_4)
- Manure Management (CH_4, N_2O)
- Other agricultural sources, including:
  - Agricultural Soils (CH_4)
  - Field Burning of Agricultural Residues (CH_4, N_2O)
  - Prescribed Burning of Savannas (CH_4, N_2O)
  - Open Burning from Forest Clearing (CH_4)

The agricultural sector is the largest contributor to global emissions of non-CO_2 greenhouse gases, accounting for 54 percent of emissions in 2005 (about 5,800 $MtCO_2e$). Exhibit 5-1 shows agricultural sector emissions by source. The sector is dominated by N_2O emissions from agricultural soils and CH_4 emissions from enteric fermentation, which accounted for 32 percent and 33 percent respectively of agricultural emissions in 2005. Emissions from agricultural soils are projected to increase by 35 percent by 2030, with its share of the sector's total emissions growing to 36 percent. Enteric fermentation emissions are expected to grow by 22 percent from 2005 to 2030, and its relative share of agricultural emissions will increase to 33 percent.

CH_4 emissions from rice cultivation, CH_4 and N_2O emissions from manure management, and other smaller agricultural sources constitute the remaining non-CO_2 emissions from this sector. Emissions from rice cultivation and manure management are projected to grow by 2 percent and 17 percent, respectively, from 2005 to 2030. This growth is moderate compared to the larger sources. The emissions from these and all other agricultural sources combined represent 31 percent of total agricultural emissions in 2030, while agricultural soils and enteric fermentation are expected to contribute the majority (69 percent).

Exhibit 5-1: Total Non-CO_2 Emissions from the Agricultural Sector, by Source ($MtCO_2e$)

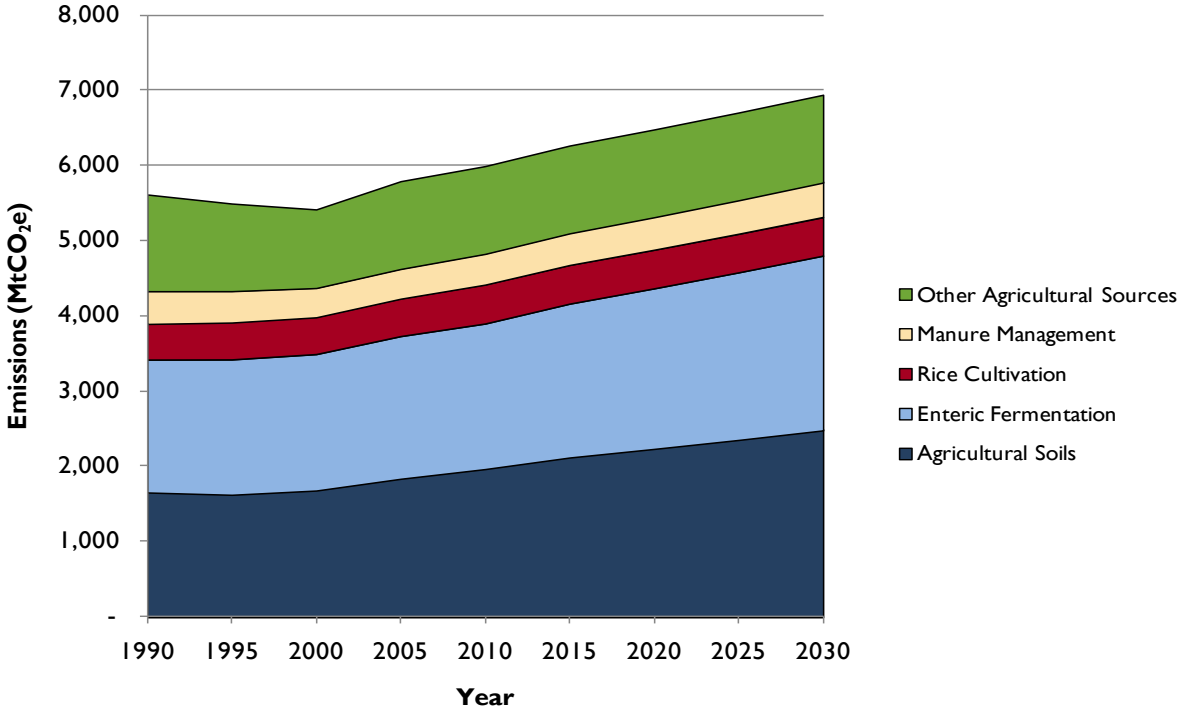
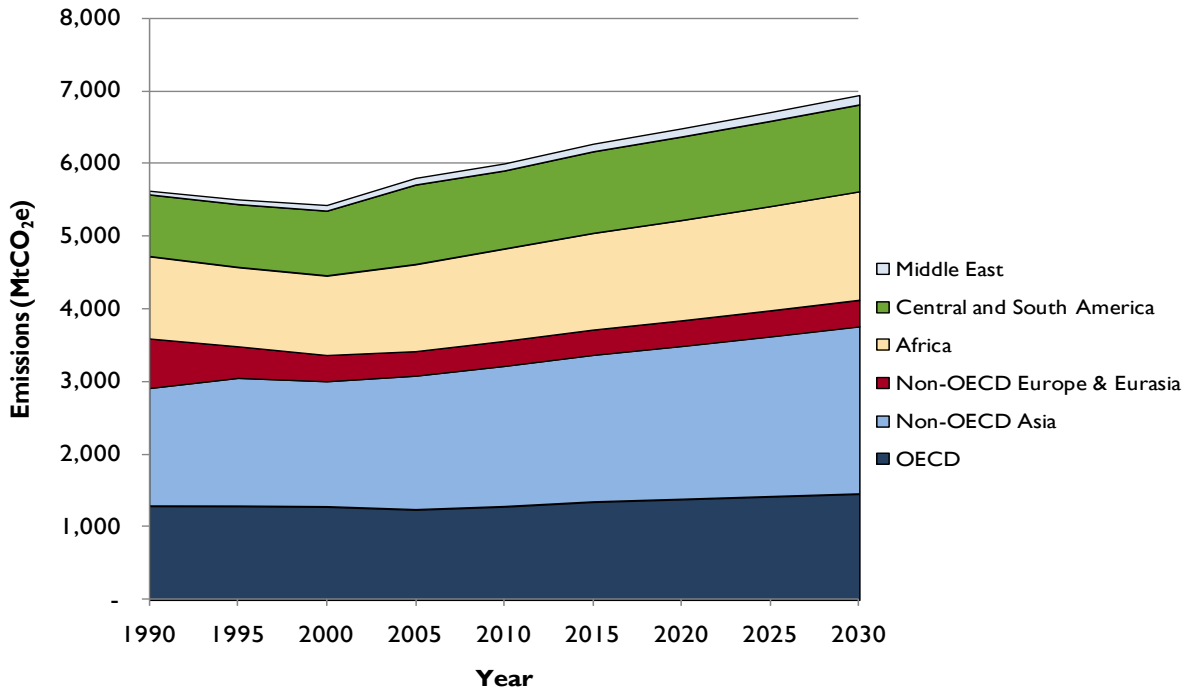


Exhibit 5-2 displays agricultural sector emissions by region. As shown in this exhibit, emissions are split fairly evenly among regions. In 2005, emissions from non-OECD Asia were larger than from other regions, at 32 percent of the agriculture total. Emissions from the OECD, Central and South America, and Africa each contributed about 20 percent.

Exhibit 5-2: Total Non-CO_2 Emissions from the Agricultural Sector, by Region ($MtCO_2e$)



The key driver for this sector is agricultural production, which is expected to increase to meet the demand of fast-growing population centers in non-OECD Asia, Central and South America, and Africa. Increases in both population and income in many areas of these regions will cause consumption of agricultural products to rise quickly. Also, changes in diet preferences, such as an increase in per-capita meat consumption, are expected to increase consumer demand for a variety of agricultural products. Increases in consumption will be met by domestic production gains from increased yields, livestock herds, and agricultural acreage, as well as imports from traditionally high-producing countries. Increased commercialization of production in less developed regions is also expected to increase fertilizer usage and livestock production capacity.

5.1 Agricultural Soils (N_2O)

5.1.1 Source Description

N_2O 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 N_2O 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 (a) the application of fertilizers and livestock wastes onto cropland and pastureland, and (b) subsequent surface runoff and leaching of nitrogen from these same sources.

Calculations in this section utilize international statistics and projections of crop production, synthetic fertilizer use, and livestock production. Synthetic fertilizer, crop residues and manure are sources of applied nitrogen which cause N_2O emissions. Emissions from this source can be mitigated by reducing or increasing the efficiency of fertilizer use, but mitigation is not assumed for this source. IPCC default factors relate

5.1.2 Source Results

Between 1990 and 2005, N_2O emissions from agricultural soil management have increased 11 percent, from 1,658 to 1,840 $MtCO_2e$. Underlying this trend are increasing crop production and increasing use of fertilizer and other nitrogen sources such as crop residues. Emissions from this source have grown in Central and South America, non-OECD Asia, Africa and the Middle East. Emissions in the OECD have remained flat, while emissions in non-OECD Europe and Eurasia have dropped by half between 1990 and 2005. Total N_2O emissions from agricultural soils are presented in Table 5-1.

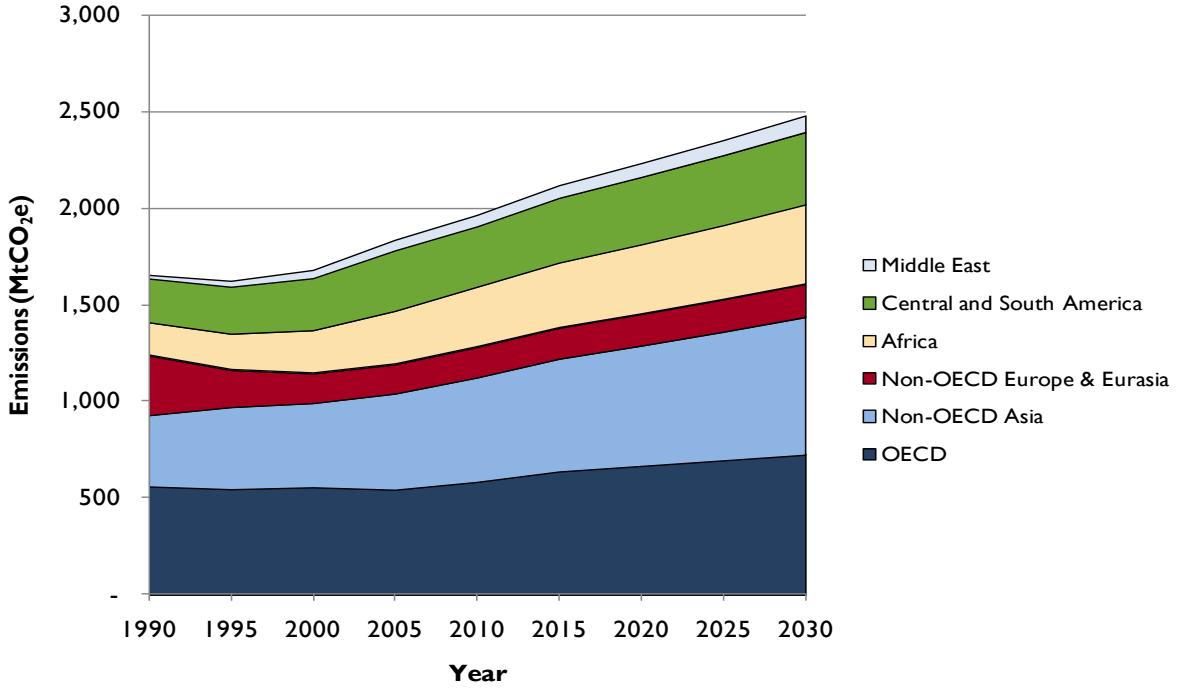
From 2005 to 2030, N_2O emissions from agricultural soils are projected to increase by 35 percent, from 1,840 to 2,483 $MtCO_2e$. This projection assumes continued increases in fertilizer usage. Over the projection period emissions are expected to increase in all regions. These regional increases are driven largely by projected emission increases in China, the United States, India, Brazil, Argentina, and Pakistan. Among OECD countries, growth will be driven by the U.S., Canada, Turkey, New Zealand, and Australia.

The primary factor for the increase in emissions illustrated in Exhibit 5-3 is the expected increase in crop and livestock production, with expanded use of synthetic fertilizers, to meet the growing fertilizer consumption requirements of non-OECD Asia, Central and South America, and Africa. Emission increases in these areas are somewhat offset by declining or slower growth in OECD countries (such as the EU and U.S.) due to constant agricultural acreage, economic and environmental agricultural policies, and the changing world market for goods. Due to 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. The following paragraphs explain some of the relevant developments that influence emissions from agricultural soils.

Table 5-1: Total N_2O Emissions from Agricultural Soils ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total N_2O	1,658.1	1,627.4	1,683.9	1,840.0	1,969.0	2,122.4	2,236.7	2,355.8	2,482.8

Exhibit 5-3: N_2O Emissions from Agricultural Soils 1990 – 2030 ($MtCO_2e$)



Overall, expected modest increases in emissions from much of the EU and more robust but slowing growth in the United States, Canada, Australia, New Zealand, and Turkey, result in a projected 36 percent rate of growth over the study period for the OECD. Many OECD countries (especially in the EU) have little opportunity for expanding crop acreage for key crops (e.g., wheat, corn) and therefore most growth in production is in the form of yield growth, which tends to have less of an impact on emissions growth than acreage increases. The market restructuring during the early 1990s in Eastern Europe, as well as in the non-EU FSU countries, resulted in an economic downturn in those countries. Because of lower farm income due to economic restructuring, farmers purchased and used less fertilizer, a main driver for emissions from this category, as well as keeping fewer livestock, leading to lower manure emissions. In the U.S., the 1990s were characterized by increases in synthetic fertilizer usage, crop and forage production, and manure production. During the projected 2010 to 2030 period, fertilizer use is expected to increase in most parts of the OECD and FSU (except Russia), leading to increases in emissions, while manure production is expected to decrease in Eastern Europe, slightly offsetting this growth.

In non-OECD Asia, Africa, Central and South America, the anticipated growth from 2010 to 2030 in agricultural soils emissions has several causes. Increases in population as well as per-capita income, particularly in China, India, and parts of Central and South America, will increase the demand for agricultural products such as cereal grains, milk, oilseed products, and meat. In addition, livestock operations are expected to become more advanced in these areas, thereby increasing demand for high-quality feed crops (e.g., corn-based). While some of this demand will be addressed in the short term through increases in imports, long term expansion of domestic production capabilities is expected. The increased commercialization of the livestock industries in these growing countries is also expected to increase livestock productive capacity and the production of livestock manure, an important component of N_2O emissions for this source category.

5.2 Enteric Fermentation (CH_4)

5.2.1 Source Description

Normal digestive processes in animals result in CH_4 emissions. Enteric fermentation refers to a fermentation process whereby microbes in an animal's digestive system ferment food. CH_4 is produced as a byproduct and can be exhaled by the animal.

Domesticated ruminants such as cattle, buffalo, sheep, goats, and camels account for the majority of CH_4 emissions in this sector. Other domesticated non-ruminants such as swine and horses also produce CH_4 as a byproduct of enteric fermentation, but emissions per animal species vary significantly. Total emissions are driven by the size of livestock populations and the management practices in use, particularly the feed regime used. The quantity, quality, and type of feed are significant determinants of CH_4 emissions. Feed intake varies by animal type, as well as by weight, age, and growth patterns for individual animals.

Calculations in this section are based on population estimates and growth projections for livestock divided among various species. Emission factors for each species are used from the 2006 IPCC guidelines. Emission factors varied between developed and developing country, and in some cases by region. No mitigation is assumed. Emission factors are held constant through the projection period despite the likelihood that changes in management practices will change average emission factors, due to the difficulty in anticipating how management practices will change over time. CH_4 emission factors from this source tend to be higher from more industrialized regions due to higher productivity per animal.

5.2.2 Source Results

Global CH_4 emissions from enteric fermentation increased by 7 percent from 1990 to 2005, from 1,764 to 1,894 $MtCO_2e$. Over this time period, global livestock populations have increased. CH_4 emissions from this source have increased most quickly in Africa and Central and South America. Emissions in non-OECD Europe and Eurasia have decreased by 46 percent between 1990 and 2005.

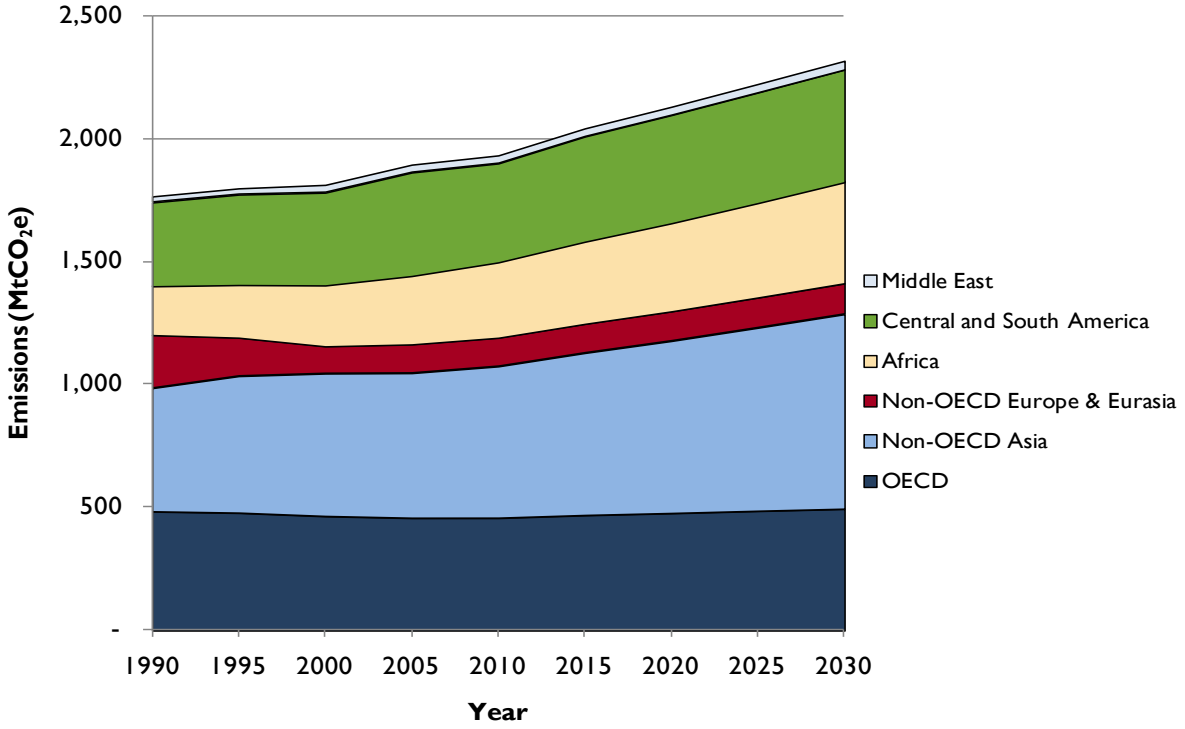
From 2005 to 2030, CH_4 emissions from enteric fermentation are projected to increase 22 percent, from 1,894 to 2,320 $MtCO_2e$. This projection assumes further increases in livestock production. It does not account for possible changes in emissions per head of livestock due to changes in management practices such as a move towards more concentrated feeding operations. The largest increases in emissions are expected in Africa and non-OECD Asia.

Between 1990 and 2005, emissions from enteric fermentation decreased in the OECD and non-OECD Europe and Eurasia, while they increased in the other regions. Emissions in all regions are expected to grow over the 2030 projection period, but will grow most quickly in Africa (48 percent), non-OECD Asia (35 percent) and the Middle East (24 percent), continuing the trend of a larger portion of world emissions shifting away from OECD countries towards non-OECD countries. In 2005, the largest five emitting countries of CH_4 from enteric fermentation were Brazil, China, India, the U.S. and Argentina.

Table 5-2: Total CH_4 Emissions from Enteric Fermentation ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	1,763.9	1,797.0	1,811.3	1,894.3	1,932.3	2,043.2	2,131.9	2,225.4	2,320.5

Exhibit 5-4: CH_4 Emissions from Enteric Fermentation 1990 – 2030 ($MtCO_2$)



Since beef, dairy, and buffalo are responsible for the majority of the world enteric fermentation emissions, historical trends in enteric fermentation CH_4 emissions follow the production cycles of these animal types. Despite the recent setbacks in the dairy and beef industries due to the global economic slowdown, the markets have started to recover, and world projections for the period 2009 through 2019 show increases in both meat and dairy product consumption, production, and trade (FAPRI, 2010). Advancing domestic beef and dairy production capabilities in some key developing countries, in combination with the maintenance of relatively high levels of production (but not necessarily high productivity growth) for large exporting countries, are expected to shape the emissions projections for this source.

Increases in per capita income are expected to drive the increase in livestock product demand, particularly in developing countries, which in turn drives domestic livestock populations and thus enteric fermentation emissions. Also, the anticipated transformation of management systems from dispersed, pasture operations to larger-sized, commercialized production is expected to increase breeding herd productivity, animal size, and overall meat production. Such transformations are occurring now throughout the developing world and will likely increase emissions, particularly in Africa and Central and South America.

In many developed countries, CH_4 emissions from enteric fermentation are expected to decline through 2030. In the EU, cattle inventories are projected to decrease, mainly in the dairy industry, as yields increase and as consumption decreases (FAPRI, 2010). During the 1990s, the farm industries in many non-OECD Europe and Eurasian countries reduced their livestock production significantly as part of their transition to market economies; however this trend slowed in 2000, and production is expected to gradually increase through 2030. A decrease in emissions for the U.S. occurred

between 1990 and 1995, resulting from increased production efficiencies, such as those occurring in the dairy industry. Recovery has been slow due to the dampening effect on export production between 2003 and 2005 due to bovine spongiform encephalopathy (BSE) cases in the industry and the current economic downturn. In China, demand and production of both meat and milk have been growing rapidly, and despite decreased milk exports following the milk scandal in 2008, emissions are projected to decline only slightly between 2005 and 2010, and then increase through 2030.

5.3 Rice Cultivation (CH_4)

5.3.1 Source Description

The anaerobic decomposition of organic matter in flooded rice fields produces CH_4. 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, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. Several factors influence the amount of CH_4 produced, including water management practices and the quantity of organic material available to decompose.

Calculations in this section utilize statistics on land area under rice cultivation and rice season length and management practices. No mitigation is assumed for this source.

5.3.2 Source Results

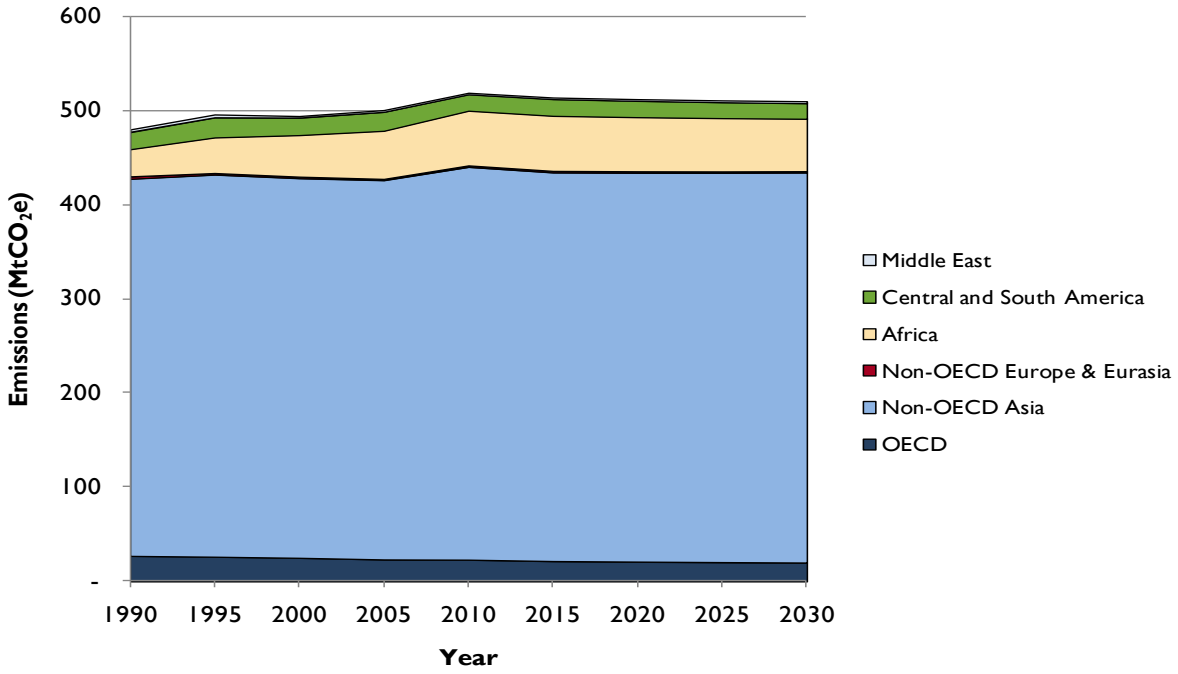
CH_4 emissions from rice production have increased 4 percent between 1990 and 2005, from 480 to 501 $MtCO_2e$ (see Table 5-3). Underlying this trend has been a similar increase in land area of harvested rice. In 2005, 90 percent of CH_4 emissions from this sector were from non-OECD Asia.

From 2005 to 2030, CH_4 emissions from this source are projected to increase 2 percent from 501 to 510 $MtCO_2e$. This projection assumes a further increase in rice area harvested over the projection period. The increase is primarily attributed to increased demand for rice due to expected population growth in rice consuming countries. Total global rice consumption is expected to rise in the projection years; however, this increase is slower than population growth because per-capita consumption decreases over the next 10 years (FAPRI, 2010). Emissions growth has also been tempered by innovations that increased rice production without increasing rice acreage–the most important determinant of rice CH_4 emissions. It is anticipated that yield growth, as opposed to acreage growth, will continue to be the main source of the production growth, with the continued development and adoption of higher-yielding rice varieties in many producing countries (FAPRI, 2010).

Table 5-3: Total CH_4 Emissions from Rice Cultivation ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	480.0	496.2	494.5	500.9	519.6	514.4	512.7	511.3	510.4

Exhibit 5-5: CH_4 Emission from Rice Cultivation 1990 – 2030 ($MtCO_2e$)



The non-OECD Asia region produces the vast majority of CH_4 emissions from rice cultivation, accounting for more than 80 percent of the emissions for this source in 2005, as illustrated in Exhibit 5-5. The single largest contributors in this region are India, China, Indonesia, Thailand, Vietnam, and Burma. Emissions from non-OECD Asia are projected to increase3 percent between 2005 and 2030. Emissions from China are expected to decrease over the projection period, while they increase from other major emitting counties in non-OECD Asia.

Thailand, Viet Nam, India, and Pakistan are projected to dominate global rice exports through the 2005 to 2030 projection period, with an estimated 75 percent or greater share of the global export market. Continued yield growth in Viet Nam and Pakistan and both yield and area growth in Thailand, Myanmar, and India is expected to increase production in those key rice-producing countries. China is expected to continue to be a significant contributor, but at a lower rate of growth due to decreases in production area (FAPRI, 2010).

5.4 Manure Management (CH_4, N_2O)

5.4.1 Source Description

Manure management produces CH_4 and N_2O. Methane is produced during the anaerobic decomposition of manure, while N_2O is produced by the nitrification and denitrification of the organic nitrogen content in livestock manure and urine. Emissions from only the managed collection, handling, storage, and treatment of manure are included here; emissions from the distribution of manure on pastures, ranges, and paddocks are included with agricultural soils emissions and are discussed in Section 5.2.

The quantity of CH_4 emitted from manure management operations is a function of three primary factors: the type of treatment or storage facility, the ambient climate, and the composition of the manure. When manure is stored or treated in liquid systems such as lagoons, ponds or pits,

anaerobic conditions can often develop and the decomposition process results in CH_4 emissions. Ambient temperature and moisture content also affect CH_4 formation, with higher ambient temperature and moisture conditions favoring CH_4 production. The composition of manure is directly related to animal types and diets. For example, milk production in dairy cattle is associated with higher feed intake, and therefore higher manure excretion rates than non-dairy cattle. Also, supplemental feeds with higher energy content generally result in a higher potential for CH_4 generation per unit of waste excreted than lower quality pasture diets. However, some higher energy feeds are more digestible than lower quality forages, which can result in less overall waste excreted. Ultimately, a combination of all these factors affects the actual emissions from manure management systems.

Nitrous oxide generation is a function of the composition of the manure, the type of bacteria involved in the decomposition process, and the oxygen and liquid content of manure. Nitrous oxide emissions occur through the processes of nitrification and denitrification, where the manure is first treated aerobically (nitrification) and then handled anaerobically (denitrification). Nitrous oxide generation is most likely to occur in dry manure handling systems that can also create pockets of anaerobic conditions.

Calculations in this section are based on population estimates and growth projections for livestock divided among various species. Nitrogen excretion and emission factors for each species are used from the 2006 IPCC guidelines and emission factors varied between regions. No mitigation is assumed. Emission factors are held constant through the projection period despite the likelihood that adoption of mitigation and changes in management practices will change average emission factors, due to the difficulty in anticipating how those changes will occur. CH_4 emission factors from this source tend to be higher from more industrialized regions due to higher productivity per animal, while nitrogen excretion per 1,000 pounds of animal are lower due to more efficient nutrient conversion.

5.4.2 Source Results

Between 1990 and 2005, CH_4 and N_2O emissions from manure management decreased by 9 percent, from 436 to 398 $MtCO_2e$. This decline was driven by the non-OECD Europe and Eurasia region, where emissions from this source decreased by 57 percent between 1990 and 2005 due to a general decline in livestock production as a result of market restructuring. Emissions increased in other country groupings.

Global CH_4 and N_2O emissions from manure management are projected to increase by 17 percent from 2005 and 2030 (see Table 5-4. Emissions are projected to increase significantly in Africa, Central and South America and the Middle East. Historically, the largest portion of GHG emissions from manure management is from the OECD, which accounted for 43 percent of all emissions in 2005. Emissions from the OECD are projected to increase by just 1 percent between 2005 and 2030. In contrast, the expected growth rates are significantly higher in other regions: Africa (38 percent), non-OECD Asia (41 percent), Middle East (24 percent), and Central and South America (28 percent). Although these regions have significantly higher growth rates, the OECD remains the top emitting region through 2030.

Table 5-4: Total CH_4 and N_2O Emissions from Manure Management ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	232.7	223.7	216.4	219.2	229.2	234.7	240.1	246.0	252.7

N_2O	203.8	194.6	174.4	179.0	183.7	191.5	198.4	205.9	213.6
Total	**436.5**	**418.3**	**390.8**	**398.3**	**412.9**	**426.2**	**438.5**	**451.9**	**466.3**

Exhibit 5-6: CH_4 Emissions from Manure Management 1990 – 2030 ($MtCO_2e$)

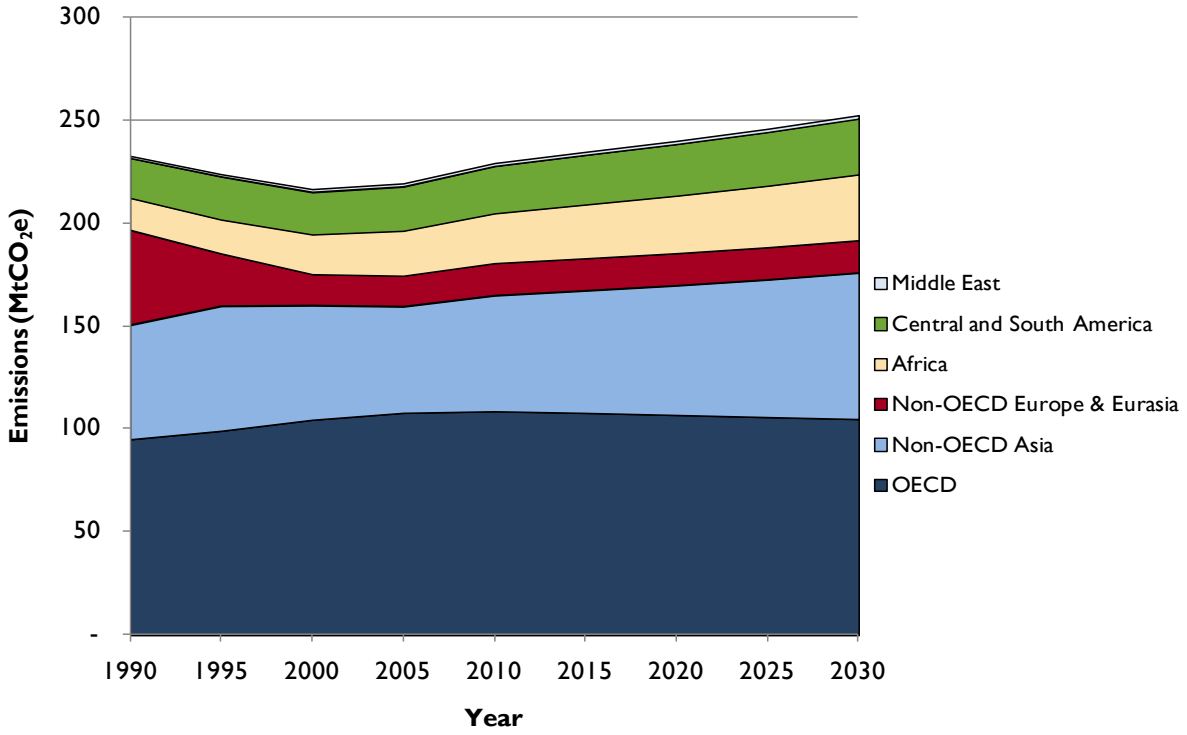
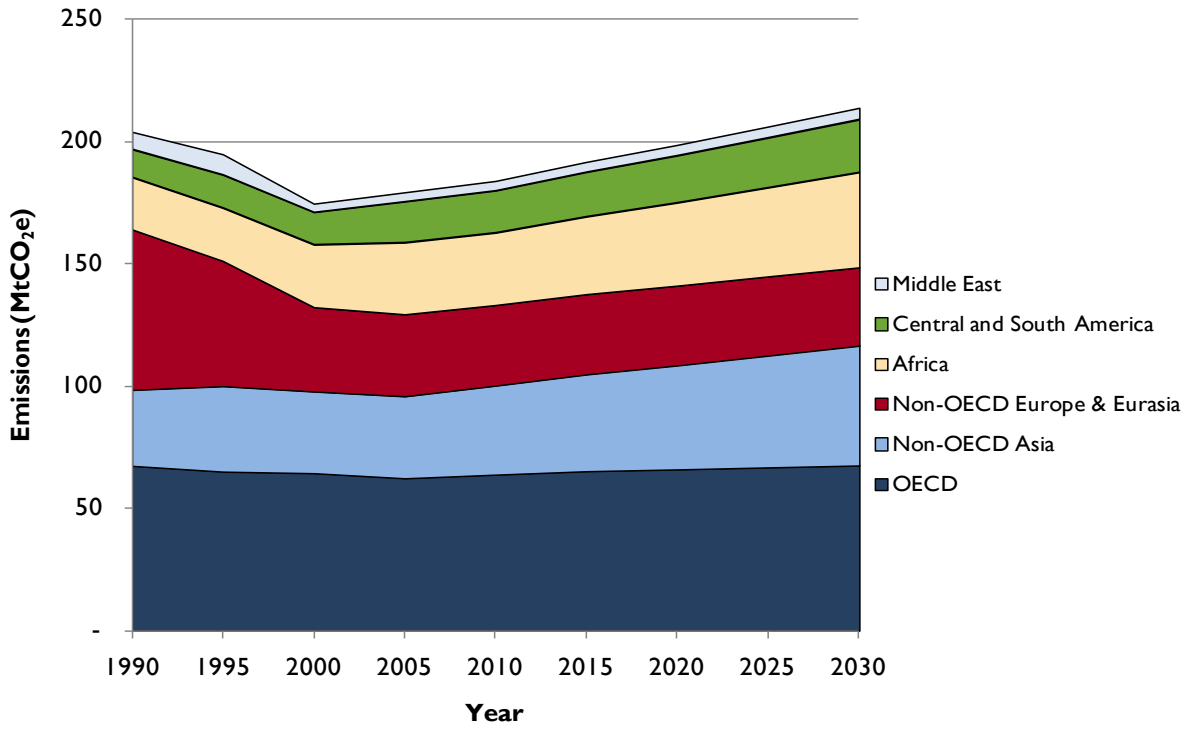


Exhibit 5-7: N_2O Emissions from Manure Management 1990 – 2030 ($MtCO_2e$)



The key factors influencing both CH_4 and N_2O emissions in this category are the growth in livestock populations necessary to meet the expected worldwide demand for dairy and meat products, and the trend toward larger, more commercialized livestock management operations. Changes in management practices can change emission factors of production. This analysis used constant emission factors reflecting current management practices but it should be noted that conversion to larger operations typically results in more liquid-based manure management systems that produce higher CH_4 emissions. Thus, the emissions estimates here may understate (or overstate) future emissions based on how management practices and the corresponding emission factors change.

All of the factors related to the increase in cattle and buffalo production described in the enteric fermentation section are pertinent to manure management as well, since livestock population increases will lead to increased manure production. In addition to cattle and buffalo production, poultry and swine livestock categories are particularly important for manure management emissions. Trends for these livestock are described in the following paragraphs.

Poultry and swine can contribute significantly to manure management emissions. Worldwide poultry production is expected to increase approximately 13 percent over the next decade (FAPRI, 2010). This increase will drive increases in N_2O emissions because of the relatively high nitrogen content of poultry waste and the manure management systems used. Continued steady growth in traditionally large poultry producing and consuming countries, such as Russia and the U.S., also contributes significantly to the projected increases in N_2O emissions for this category.

Swine production can have a large influence on CH_4 emissions from manure management. Global trade in pork products is expected to increase by 28 percent over the next decade (FAPRI 2010), driving changes in population and production practices. Continued transformation of the pork

industry from locally dispersed individual producers to larger commercialized operations is expected to increase both production and livestock population. In particular, this transformation is expected to take place in countries such as China and Brazil, which are both expected to have high growth rates over the next decade (FAPRI 2010). In addition, larger commercialized operations tend to utilize more liquid-based manure management systems, which generate more CH_4 emissions than smaller, individual feedlot operations. In the U.S., one of the largest and most commercialized pork producing countries in the world, swine are responsible for almost half of the CH_4 emissions from manure management primarily because a large portion of the manure is handled with liquid-based systems. As other key pork producing countries transform to larger management systems, the trend will likely be toward increasing CH_4 emissions.

5.5 Other Agriculture Sources (CH_4, N_2O)

5.5.1 Source Description

This category includes emission sources from the agricultural sector that are relatively small compared to the sector overall. The data presented in this chapter include the following sources of CH_4 and N_2O:

- Agricultural Soils (CH_4)
- Field Burning of Agricultural Residues (CH_4, N_2O)
- Prescribed Burning of Savannas (CH_4, N_2O)
- Open Burning from Forest Clearing (CH_4)

Field burning, prescribed burning, and open burning constitute the majority of emissions for this source category, whereas agricultural soils contribute a small fraction of emissions.

5.5.2 Source Results

Total emissions from other agricultural sources are shown in Table 5-5. Africa is the largest contributor of emissions for this source category, accounting for about 46 percent of emissions in 2005. Central and South America and non-OECD Asia are the second and third largest contributors for this source category, contributing an average of 26 percent and 22 percent in 2005, respectively. Data for other agricultural sources are based only on country reports, and so are not fully comparable between countries or to data in the remainder of this report since emissions are not calculated for countries not reporting emissions data.

Table 5-5: Total CH_4 and N_2O Emissions from Other Agricultural Sources ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	506.6	420.0	344.0	421.0	421.0	421.0	421.0	421.0	421.0
N_2O	776.7	743.0	699.3	744.1	744.1	744.1	744.1	744.1	744.1
Total	**1,283.3**	**1,163.0**	**1,043.3**	**1,165.1**	**1,165.1**	**1,165.1**	**1,165.1**	**1,165.1**	**1,165.1**

Exhibit 5-8 and Exhibit 5-9 illustrate trends in CH_4 and N_2O emissions for this category.

Exhibit 5-8: CH_4 Emissions from Other Agricultural Sources 1990-2030 ($MtCO_2e$)

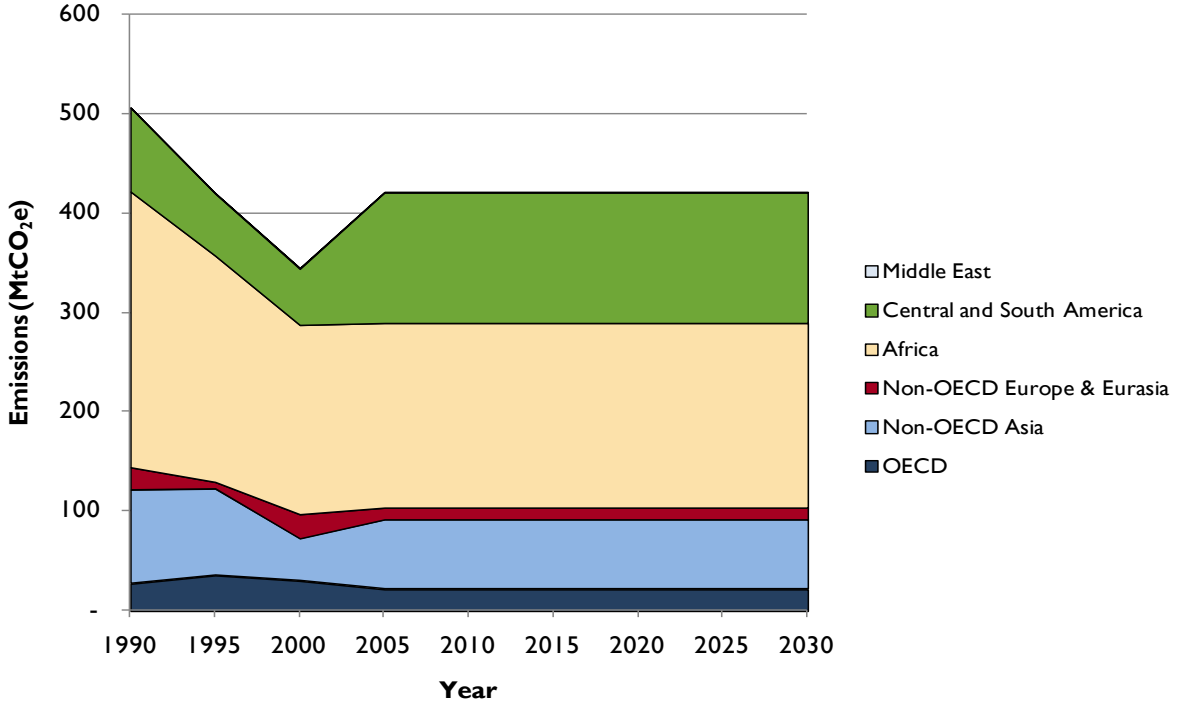
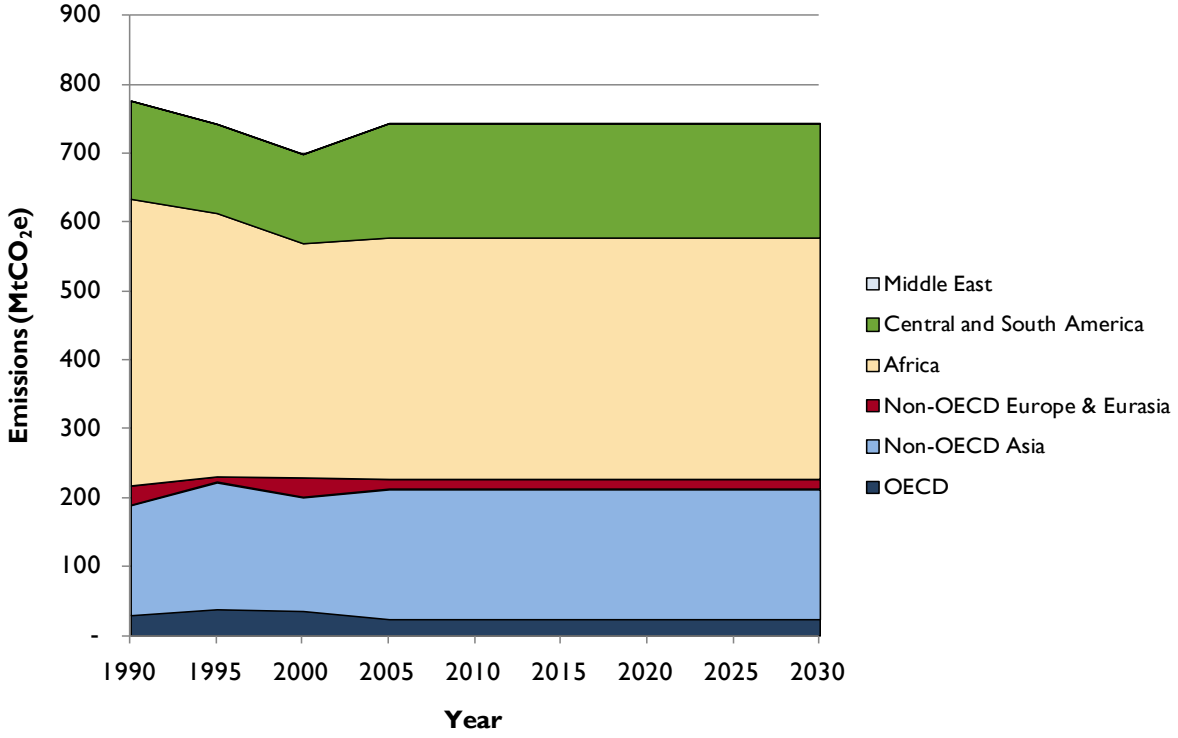


Exhibit 5-9: N_2O Emissions from Other Agricultural Sources 1990-2030 ($MtCO_2e$)



6 Waste

This section presents global CH_4 and N_2O emissions for 1990 to 2030 for the following waste sector sources:

- Landfilling of Solid Waste (CH_4)
- Wastewater (CH_4)
- Human Sewage – Domestic Wastewater (N_2O)
- Other Waste Sources (CH_4, N_2O), including:
    - Miscellaneous Waste Handling Processes (CH_4, N_2O).

The waste sector accounted for 13 percent of total non-CO_2 emissions in 2005, and is anticipated to drop to 11 percent of emissions by 2030. Exhibit 6-1 shows the waste sector emissions by source. As shown in Exhibit 6-1, the two largest sources of non-CO_2 GHG emissions within the waste sector are landfilling of solid waste and wastewater, together contributing 92 percent of emissions throughout the 1990 to 2030 period. Landfilling of solid waste contributed 58 percent of total waste sector emissions in 2005, while wastewater contributed 35 percent of emissions. Out of all sources, landfilling was the fourth largest individual source of non-CO_2 GHG emissions in 2005, at 794 $MtCO_2e$.

Exhibit 6-1: Total Non-CO_2 Emissions from the Waste Sector, by Source ($MtCO_2e$)

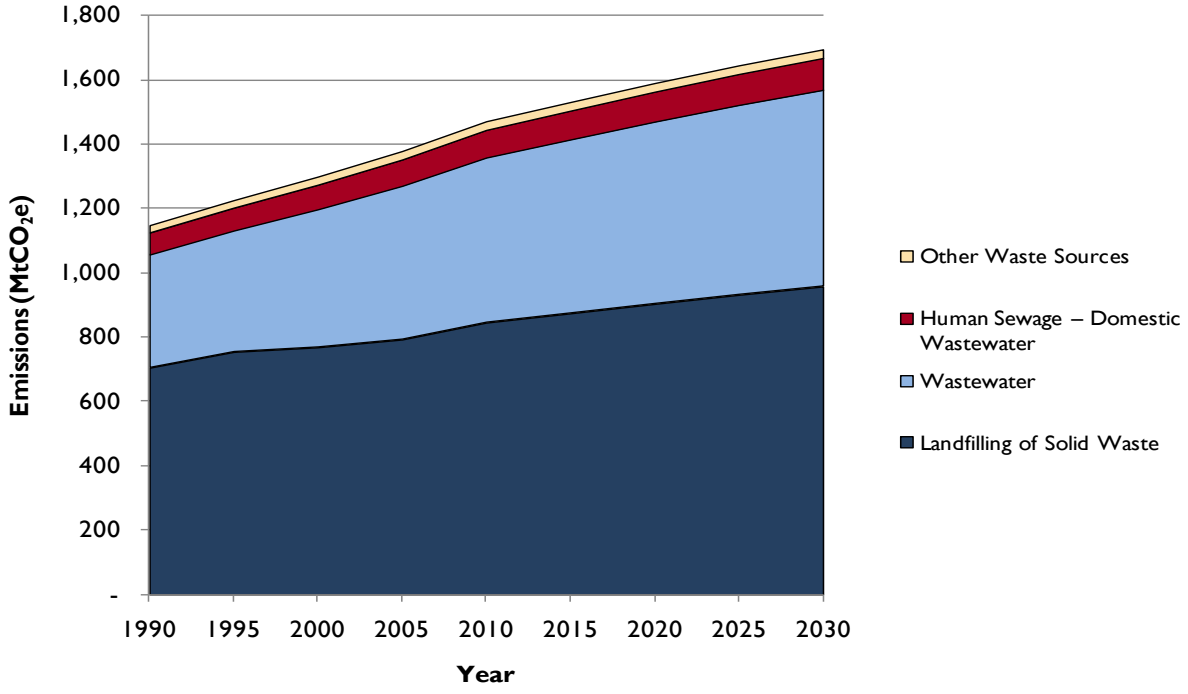
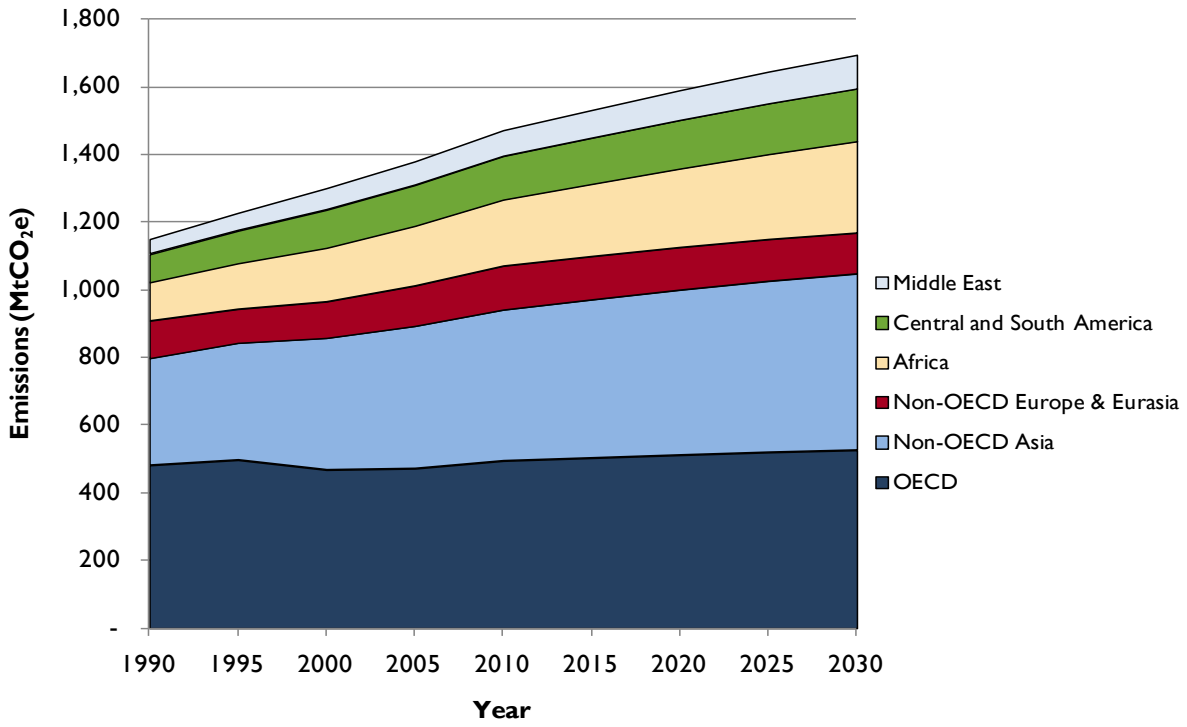


Exhibit 6-2 shows waste sector emissions by region. The OECD and non-OECD Asia were the largest contributors to waste sector non-CO_2 emissions, accounting respectively for 34 percent and 31 percent of emissions in 2005. Non-CO_2 emissions from the OECD are expected to decrease to 31 percent of the total in 2030, still the largest-emitting region.

Exhibit 6-2: Total Non-CO_2 Emissions from the Waste Sector, by Region ($MtCO_2e$)



6.1 Landfilling of Solid Waste (CH_4)

6.1.1 Source Description

CH_4 is produced and emitted from the anaerobic decomposition of organic material in landfills. The major drivers of emissions are the amount of organic material deposited in landfills, the extent of anaerobic decomposition, the thickness as well as the physical and chemical properties of the landfill cover materials, the seasonal variation in methane oxidation rates[1], and the level of landfill CH_4 collection and combustion (e.g., energy use or flaring)[2]. The amount of waste deposited in landfills can be affected by waste-reduction and recycling efforts. Because organic material deep within landfills takes many years to completely decompose, past landfill disposal practices greatly influence present day emissions. Developed countries are experiencing a stabilization or decline in landfill wastes due to regulations that encourage such practices. Developing countries, on the other hand, are expected to face increasing rates of landfill methane due to increased urbanization and a parallel increase in controlled landfilling (IPCC, 2007). However, public scrutiny of GHGs from landfilling (and other waste management activities) is increasing in both developed and developing countries (Bogner and Spokas, 2010).

[1] Landfill methane oxidation reflects the amount of methane that is oxidized or converted to CO_2 in the soil or other materials that cover the landfilled waste.

[2] For additional information on landfill methane emissions refer to IPCC, 2007; Bogner and Spokas, 2010; and Scheutz et al., 2009.

Emissions projections for this source utilize National Communications projections where available and a combination of activity data and emission factors to project emission estimates where country-reported projected data was not available. Emission factors were generated using the IPCC 2006 Waste Model.

International voluntary programs encourage measures which can reduce CH_4 emissions through the capture and beneficial reuse of landfill CH_4 gas, but those programs are not explicitly included in these estimates. Waste reduction programs, as well as CH_4 recovery and use impact the amount of CH_4 that is actually released to the atmosphere. Mitigation measures include installing landfill gas collection systems. The collected landfill CH_4 gas can then be flared, used to generate heat and/or electricity, or sold for pipeline injection. Over the last couple of decades, although landfill methane emissions have continued to increase, growth in these emissions has declined due to decreasing landfilling rates, particularly in Europe, and increasing landfill gas recovery rates in many countries (IPCC 2007). Additional mitigation measures contributing to landfill gas recovery include increased use of biocovers and geomembrane composite covers to enhance CH_4 oxidation.

The IPCC 2006 Guidelines recommend using a first-order decay (FOD) method for the simplest tier 1 estimates, replacing the previous mass balance method recommended by IPCC 1996 Guidelines and used for the GER 2006 report. Emissions calculations for non-reporting countries use the Tier 1 FOD method; however, it is possible that not all country-reported data has used this relatively recent change in the methodological guidance, thus limiting comparability across country estimates.

6.1.2 Source Results

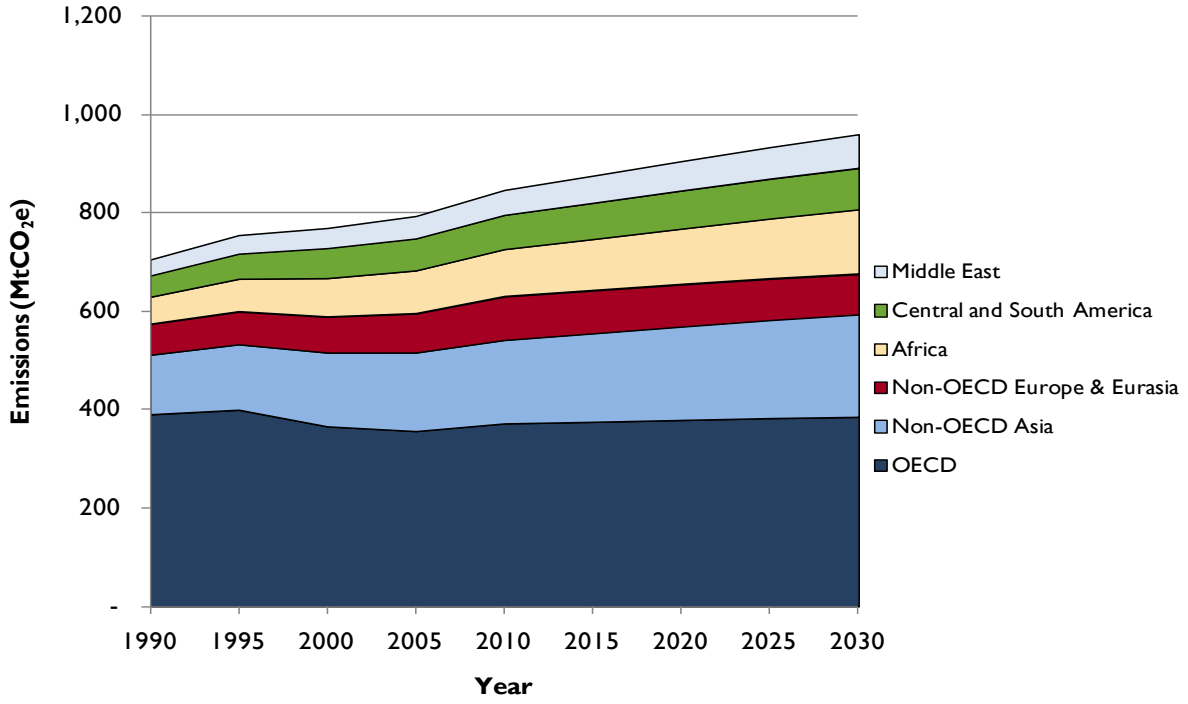
Between 1990 and 2005, global CH_4 emissions from landfilling of solid waste are estimated to have increased by about 12 percent, from 706 to 794 $MtCO_2e$ (see Table 6-1). Driving factors for landfill emission trends are growing populations, increases in personal incomes, and expanding industrialization, all of which can lead to increases in the amount of solid waste generated for a country. Over this time period emissions have decreased in OECD countries. Emissions in all other regions have increased (see Exhibit 6-3).

From 2005 to 2030 emissions are projected to increase by about 21 percent from 794 to 959 $MtCO_2e$ (see Table 6-1). The projected increase in emissions shows significant shifts in contributions to landfill emissions. Emissions from the OECD are projected to increase by 8 percent between 2005 and 2030, decreasing from 45 percent to 40 percent of the global emissions for this source. By 2030, the following two regions are projected to contribute more than a 10 percent share of global emissions: Africa (14 percent) and non-OECD Asia (22 percent). Countries with fast-growing economies and populations are expected to contribute more to the global CH_4 total from landfills as their economies grow and waste generation rates increase. Countries with more steady-state economic growth, and small or even declining population growth rates, are likely to experience minimal growth in landfill emissions. The OECD countries emitted about 45 percent of the global CH_4 produced from the landfilling of solid wastes in 2005, as shown in Exhibit 6-3. In that same year, the remaining regions each contributed less than 20 percent of the CH_4 emissions for this source category. Within the OECD, the U.S. is the largest source of emissions from the landfilling of solid waste. In 2005, the U.S. emitted 113 $MtCO_2$ e. of CH_4, which is about 14 percent of the global total.

Table 6-1: Total CH_4 Emissions from Landfilling of Solid Waste ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	706.1	755.4	769.8	794.0	846.7	875.6	905.0	933.3	959.4

Exhibit 6-3: CH_4 Emissions from Landfilling of Solid Waste 1990 – 2030 ($MtCO_2e$)



The decline in emissions from 1990 to 2005 in the OECD is largely due to non-climate regulatory programs and the collection and flaring or use of landfill CH_4. In many OECD countries, landfill CH_4 emissions are not expected to grow, despite continued or even increased waste generation, because of non-climate change related regulations that result in mitigation of air emissions, collection of gas, or closure of facilities. A major driver of CH_4 emissions in the OECD is the European Union Landfill Directive, which limits the amount of organic matter that can enter solid waste facilities. Although organic matter is expected to decrease rapidly in the EU, emissions occur as a result of total waste in place and will gradually decline over time.

In regions other than the OECD, an increase in CH_4 emissions is projected. In these regions, solid waste is expected to be increasingly diverted to managed landfills as a means of improving overall waste management. The combined effects of rapid economic change, expansive growth policies, and population increase, particularly in the urban centers of developing countries, will result in changing consumption patterns and increases in waste generation. Per-capita waste generation rates can increase by three or four times in the transition from a rural, low-income scenario to higher income urban-based populations. Areas showing high growth in emissions between 1990 and 2030 (e.g., Middle East at 141 percent growth, Africa at 112 percent, and non-OECD Asia at 67 percent) are all undergoing such transformations.

6.2 Wastewater (CH_4)

6.2.1 Source Description

CH_4 is emitted both from deliberate venting and fugitive emissions during the handling and treatment of domestic and industrial wastewater. The organic material in the wastewater produces CH_4 when it decomposes anaerobically. Most developed countries rely on centralized aerobic wastewater treatment to handle their domestic wastewater, so that CH_4 emissions are small and incidental. However, in developing countries with little or no collection and treatment of wastewater, anaerobic systems or disposal environments such as latrines, open sewers, or lagoons are more prevalent. Industrial wastewater can also be treated anaerobically, with significant CH_4 being emitted from those industries with high organic loadings in their wastewater stream, such as food processing and pulp and paper facilities. While country-reported estimates include both domestic and industrial wastewater, the emissions estimates calculated using Tier 1 methodology only include domestic wastewater.[3]

Emissions projections for this source utilize National Communications projections were available. Where NC data was not available, emissions were projected from UNFCCC historical data using population growth rates.

CH_4 emissions from wastewater can be reduced through improved wastewater treatment practices include reducing the amount of organic waste anaerobically digested and by flaring or using CH_4 from anaerobic digesters for cogeneration or other beneficial reuse. Such emission reduction activities are not widespread 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 CH_4 capture from anaerobic digesters that would result in a reduction of emissions.

6.2.2 Source Results

Between 1990 and 2005, global CH_4 emissions from wastewater are estimated to have increased by about 35 percent, from 352 to 477 $MtCO_2e$ (see Table 6-2). The main driver for increasing domestic wastewater emissions is population growth, particularly growth associated with countries that rely on anaerobic treatment and collection systems such as latrines, septic tanks, open sewers, and lagoons. Most developed countries have an extensive infrastructure to collect and treat urban wastewater, in which the majority of systems rely on aerobic treatment with minimal CH_4 production and thus less effect on the emissions trend. In contrast, there is widespread use of less advanced, anaerobic systems in some of the fastest growing parts of the world. Consequently, the largest growth in emissions has been in Africa, the Middle East, and Central and South America (see Exhibit 6-3).

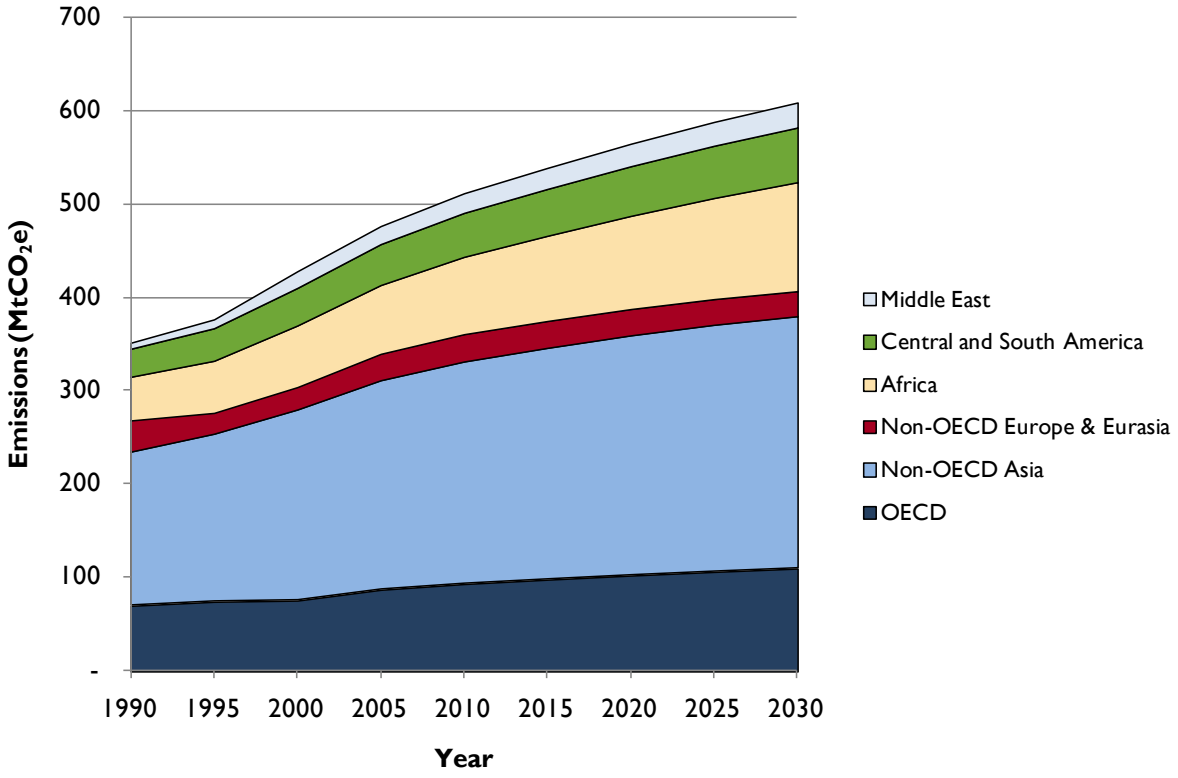
From 2005 to 2030 emissions are projected to increase by about 28 percent from 477 to 609 $MtCO_2e$ (see Table 6-2). The projected rate of increase is expected to be highest in the same regions where emissions grew most quickly over the historical period: Africa, the Middle East, and Central and South America. Emissions from Africa are projected to increase by about 58 percent between 2005 and 2030, 39 percent for the Middle East, and 34 percent for Central and South America.

[3] 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.

Table 6-2: Total CH_4 Emissions from Wastewater ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total CH_4	351.9	376.9	428.4	476.7	511.8	538.9	564.7	588.0	608.8

Exhibit 6-3: CH_4 Emissions from Wastewater 1990 – 2030 ($MtCO_2e$)



A majority of domestic wastewater goes uncollected and untreated in large portions of the non-OECD Asia and Africa regions, with an even larger share in rural areas. Much of this untreated wastewater is found in open sewers, pits, latrines, or lagoons where there is greater potential for CH_4 production. For example, nearly 74 percent of China's domestic wastewater emissions are estimated to come from latrines, with the majority of wastewater generated in rural China being untreated. The largest share of India's estimated emissions also comes from latrines (62 percent), but open sewers contribute a sizable amount as well (34 percent). Like India, most of Indonesia's emissions come from latrines and open sewers. As long as populations grow significantly without large scale advances in wastewater treatment, these areas will continue to have a major influence on the upward trend in wastewater CH_4 emissions. The impact of urban center growth in these regions, however, may offset this trend if migrating rural populations are served by more advanced urban treatment systems.

Less advanced treatment systems are still widely used in some developed countries. In the U.S., for example, septic tanks are estimated to be responsible for 65 percent of the domestic wastewater emissions, though only 25 percent of treatment. Septic tanks are utilized in many parts of the developed world where centralized sewer infrastructure is not available; however, their usage is not expected to increase significantly in the future since there are economic and site considerations that limit their widespread applicability.

6.3 Human Sewage – Domestic Wastewater (N_2O)

6.3.1 Source Description

Domestic wastewater is also a source of N_2O emissions. Domestic wastewater includes human waste as well as flows from shower drains, sink drains, washing machines and other domestic effluent. The wastewater is transported by a collection system to an on-site, decentralized wastewater treatment (WWT) system, or a centralized WWT system. Decentralized WWT systems are septic systems and package plants. Centralized WWT systems may include a variety of processes, ranging from treatment in a lagoon to advanced tertiary treatment technology for removing nutrients. After processing, treated effluent may be discharged to a receiving water environment (e.g., river, lake, estuary) applied to soils, or disposed of below the surface.

N_2O may be generated during both nitrification and denitrification of the nitrogen present in the wastewater effluent, usually in the form of urea, ammonia, and proteins. These are converted to nitrate via nitrification, an aerobic process converting ammonia-nitrogen into nitrate (NO_3-). Denitrification occurs under anoxic conditions (without free oxygen), and involves the biological conversion of nitrate into dinitrogen (N_2). N_2O can be an intermediate product of both processes, but is more often associated with denitrification.

Emissions projections for this source utilize National Communications projections were available. Where NC data was not available, emissions were projected from UNFCCC historical data using population growth rates. Emissions may be linked to treatment type (lagoons versus advanced treatment such as nitrification/denitrification plant), however not enough information is available to account for advanced treatment methods. The IPCC default methodology uses the same emission factor for all wastewater generated. Therefore, the total quantity of wastewater generated, regardless of treatment type, is the principle factor.

Some industries produce wastewater with significant nitrogen loadings that is discharged to the city sewer, where it mixes with domestic, commercial, and institutional wastewater. However, emissions from these sources have not been estimated, unless countries have reported these emissions within either the human sewage or wastewater source categories. This methodology does not take into account changes to dietary standards over time in developing countries, which could lead to emissions increases.

6.3.2 Source Results

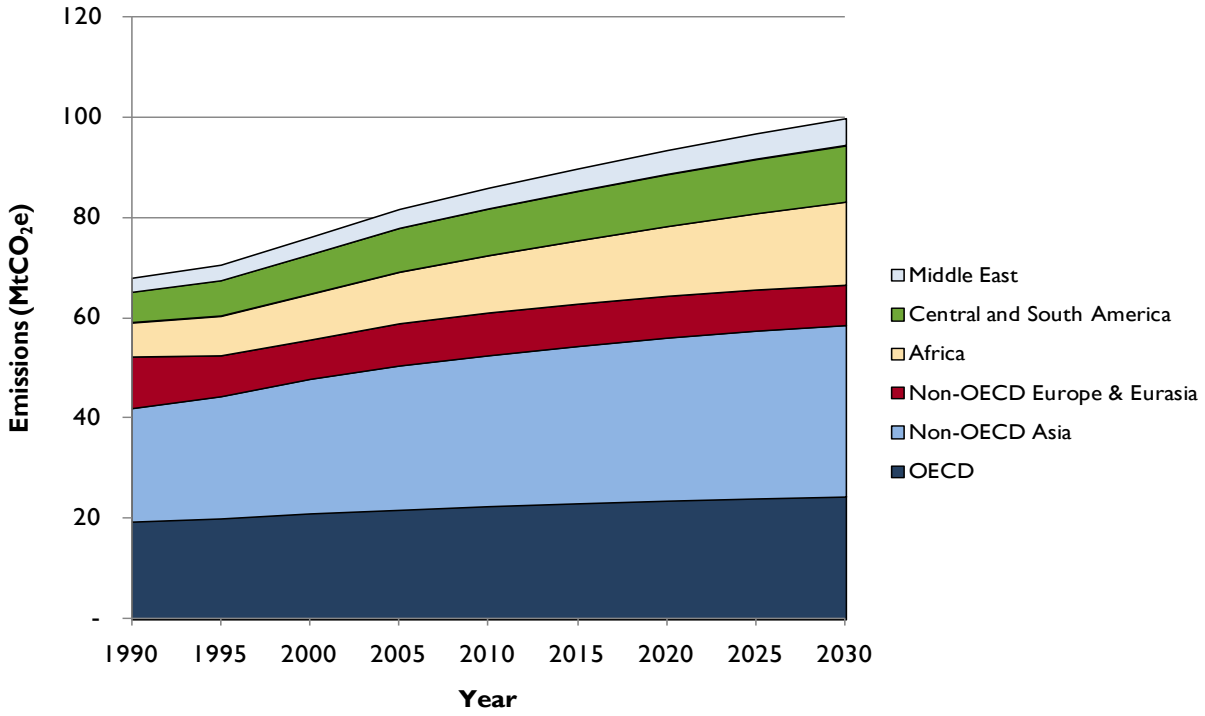
Between 1990 and 2005, global N_2O emissions from human sewage are estimated to have increased by about 20 percent, from 68 to 82 $MtCO_2e$ (see Table 6-4). The main driver for human sewage emissions is population increase.

From 2005 to 2030 emissions are projected to increase by about 22 percent from 82 to 100 $MtCO_2e$ (see Table 6-4). Emissions from this source are projected to rise most quickly in Africa, the Middle East, and Central and South America. Emissions from Africa are projected to increase by about 62 percent between 2005 and 2030, 41 percent for the Middle East, and 29 percent for Central and South America. In 2030, it is estimated non-OECD Asia and the OECD continue to be the largest contributing regions to N_2O emissions from human sewage, while declining slightly in their overall share of world emissions to 24 percent and 34 percent respectively. In 2030, Africa is projected to contribute 17 percent of emissions, and Central and South America is projected to contribute 11 percent.

Table 6-4: Total N_2O Emissions from Human Sewage – Domestic Wastewater ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
Total N_2O	68.0	70.6	76.1	81.7	85.9	89.8	93.4	96.8	99.8

Exhibit 6-4: N_2O from Human Sewage – Domestic Wastewater 1990 – 2030 ($MtCO_2e$)



In addition to population, rise in per-capita income tends to increase the amount of nitrogen available in the wastewater generated due to increases in per-capita protein consumption. Developed countries can have more than double the annual protein consumption of developing countries. However, per capita consumption of meat and dairy products changes fastest in countries where current consumption levels are low, rapid urbanization is occurring, and incomes are growing rapidly from a low base. Therefore, the long term trend of N_2O emissions from human sewage will be largely impacted by fast-growing economies such as China and India.

6.4 Other Waste Sources (CH_4, N_2O)

6.4.1 Source Description

This category includes emission sources from the waste sector that are relatively small and are thus grouped together. The data presented here include CH_4 and N_2O emissions from miscellaneous waste handling processes.

6.4.2 Source Results

This source is relatively small, emitting approximately 26 $MtCO_2e$ in 2005. However, emissions were not calculated for all countries. Non-OECD Asia is the largest contributor to emissions from miscellaneous waste handling processes, accounting for approximately 39 percent of emissions. Table 6-6 and Exhibit 6-5 and Exhibit 6-6 illustrate trends in CH_4 and N_2O emissions for this category.

Table 6-6: Total CH_4 and N_2O from Other Waste Sources ($MtCO_2e$)

Gas	1990	1995	2000	2005	2010	2015	2020	2025	2030
CH_4	13.4	13.6	14.7	15.2	15.5	15.5	15.5	15.5	15.5
N_2O	8.9	9.6	10.5	11.2	11.4	11.4	11.4	11.4	11.4
Total	**22.3**	**23.2**	**25.1**	**26.4**	**26.9**	**26.9**	**26.9**	**26.9**	**26.9**

Exhibit 6-5: CH_4 Emissions from Other Waste Sources 1990 – 2030 ($MtCO_2e$)

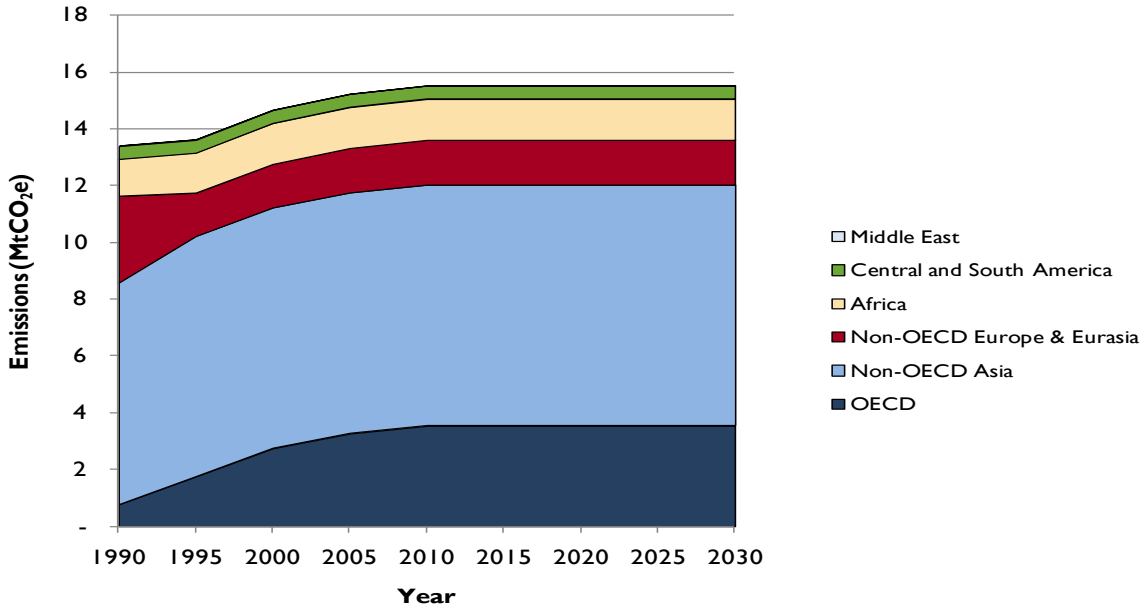
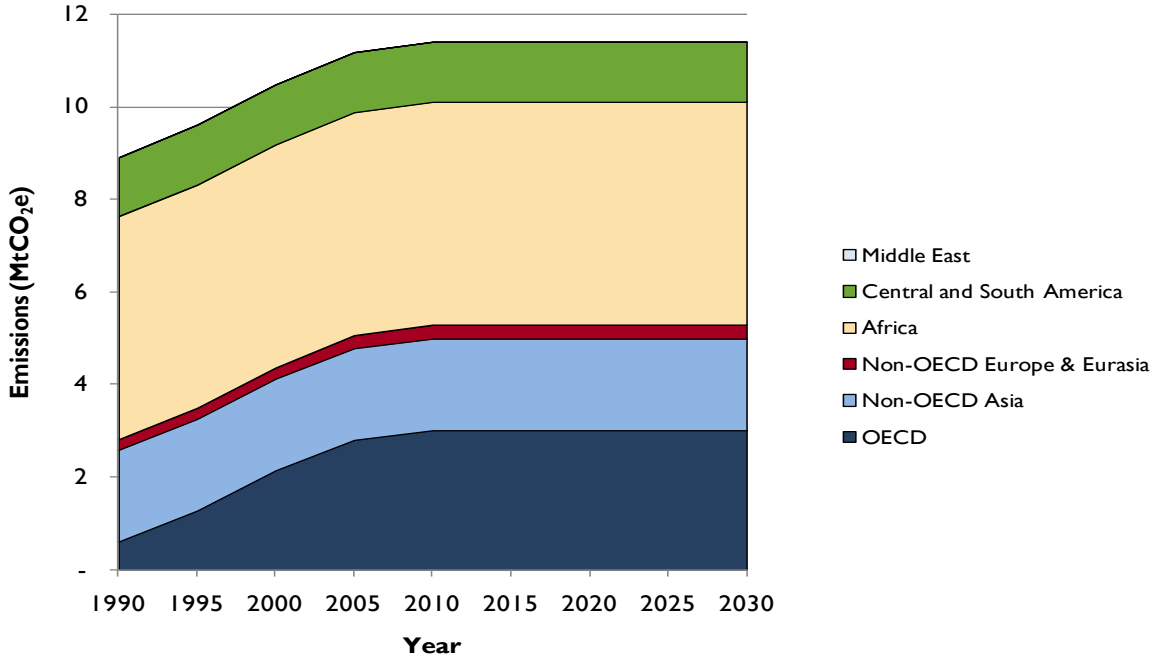


Exhibit 6-6: N_2O Emissions from Other Waste Sources 1990 – 2030 ($MtCO_2e$)



7 Methodology

This chapter outlines the methodologies used to compile and estimate category and country-specific historical and projected emissions of CH_4, N_2O, and F-GHGs. The preferred approach for estimating historical and projected emissions is to use a hierarchy of country-prepared, publicly-available reports. If country-supplied data are not available, EPA estimates emissions consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (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* (IPCC Guidelines) (IPCC, 2006).

A primary source of data for historical emission estimates was the UNFCCC flexible query system data (UNFCCC, 2012). The UNFCCC flexible query system contains historical CH_4 and N_2O emission estimates for Annex I (A1) and non-A1 countries, reported to the UNFCCC (from A1 National Inventories Common Reporting Format files and non-A1 National Communication reports). The CRF data obtained through the UNFCCC flexible query system (UNFCCC, 2012) contain reported national inventory data from 1990 through 2009. Data for non-A1 countries obtained through the UNFCCC flexible query system contained data reported through country National Communication reports. As identified by the UNFCCC, Annex I countries include all OECD countries in 1992, plus countries with economies in transition and most of Central and Eastern Europe. Annex I countries are noted in Exhibit 1-2 and Appendix J. The hierarchy of data sources and an overview of the methods used to augment missing historical and projected estimates are discussed below followed by a detailed discussion of the methodology associated with each source category and gas.

This report does not describe in detail the methodology used to generate the publicly-available data. However, the CRF inventory data obtained through the UNFCCC flexible query system are generally comparable across countries because they are based on IPCC methodologies and are reported for a standard list of IPCC source categories. Although the CRFs provide the latest historical GHG emissions data for Annex I countries, they do not contain projected emissions. A preferred source for projected emissions is the National Communications. The National Communications are documents that were submitted by each Party to the UNFCCC Secretariat to report on steps taken to implement the Convention; they contain emissions and projections to various years, up to 2035. EPA used the Fifth National Communications for Annex I countries and the First, Second, and/or Third National Communications for non-Annex I countries for this analysis. The Fifth National Communications for Annex I countries were submitted primarily in 2009 and 2010. The non-Annex I countries have a more flexible schedule, with submissions of First, Second, and/or Third National Communications from 1997 to 2009. The projected information from the National Communication is adjusted to be compatible with the most recent inventory data, if necessary.

Data Sources for Historical and Projected Emissions

CH_4 and N_2O General Methodology

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

Historical Emissions (1990, 1995, 2000, 2005)

Annex I Countries

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

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

Non-A1 Countries

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

Projected Emissions (2010, 2015, 2020, 2025, and 2030)

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

If an NC had projections for a sector but not a source, EPA used the relative proportion of emissions for the latest year of historical emissions to disaggregate projected emissions for a source. For example, if France projected CH_4 emissions from agriculture to 2030 but does specify what portion is from manure management, EPA took the proportion of emissions that manure

contributes to agriculture CH_4 emissions in France's 2007 GHG Inventory, assume this proportion remains constant for 2030, and apply this to the 2030 agriculture estimate.

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

High Global Warming Potential Gas Emissions

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

7.1 Energy

7.1.1 Natural Gas and Oil Systems (CH_4)

If country-reported emission estimates were not available or the data are insufficient, EPA used the 2006 IPCC Tier 1 methodology (IPCC, 2006) to estimate emissions. The Tier 1 basic equation to estimate fugitive CH_4 emissions from oil and natural gas production, transmission, and distribution systems is as follows:

Fugitive CH_4 Emissions = (Annual Oil Production x Emission Factors + Annual Crude Oil Refined x Emission Factor) + (Annual Natural Gas Production x Emission Factors + Annual Natural Gas Consumption x Emission Factors)

Assuming that the emission factors do not change, the driver for determining fugitive CH_4 emissions from oil and natural gas is the respective production and consumption of these fuels.

Historical Emissions

Activity Data

- EPA obtained historical natural gas and oil production and consumption data, and refinery capacity data from U.S. Energy Information Agency (EIA) for 1990 through 2005 (EIA, 2009). EPA assumed that refinery utilization is equal to the ratio of oil production to refinery capacity.

Emission Factors and Emissions

- EPA used 2006 IPCC Guidelines default factors for natural gas production (IPCC, 2006), natural gas consumption, oil production, oil refining, and venting and flaring for 1990, 1995, 2000, and 2005 emissions. Where IPCC guidelines provided only ranges for emissions factors (as opposed to central estimates) the midpoint of the range was used.
- EPA multiplied appropriate oil and natural gas production and consumptions and refining statistics for 1990, 1995, 2000, and 2005 by IPCC (IPCC, 2006) default factors.
- If country-provided historical data combined oil and natural gas emissions into one estimate, EPA determined the percentage of emissions generated from each industry sector using the IPCC Tier 1 methodology. EPA applied this percentage to country-provided historical data to determine the approximate emissions associated with each industry.

- For missing historical years, EPA extrapolated emissions based on changes in oil and natural gas production and consumption from EIA (EIA, 2009).

If emissions are not reported and EIA production data are not available, EPA assumed zero emissions for this source.

Projected Emissions

Activity Data

Projections of natural gas and oil production and consumption were available from the EIA (EIA, 2009). EPA used growth rates as provided by EIA "reference case" projections for 2005-2010, 2010-2015, 2015-2020, 2020-2025, and 2025-2030. These growth rates were available by country or region.

Emissions

EPA applied EIA consumption projected growth rates to activity factors closely related to consumption (such as transportation of fuels), and applied EIA production projected growth rates to activity factors (such as production and processing of oil and gas) which are closely related to production for each time period and region. Where emissions were estimated using IPCC Tier 1 emission factors, the emission factors were applied directly to the projected activity data. For countries that submitted National Communication data, production growth rates in barrels of oil equivalents were used to project their historical emission data. Specifically for the U.S., projected emissions utilize the updated 2011 U.S. Greenhouse Gas Inventory data as a basis for 2010 projections and Tier 1 emission factor projections from 2015 to 2030.

Uncertainties

The greatest uncertainties are due to the use of default emission factors, and difficulties in projecting oil and natural gas consumption and production through 2030 for rapidly changing global economies such as those in the FSU and developing Asia. In addition, CH_4 emissions from oil and natural gas systems are not linearly related to throughput, so the IPCC Tier 1 methodology and emission factors can lead to overestimates.

Table B-2 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.1.2 Coal Mining Activities (CH_4)

The basic equation to estimate fugitive CH_4 emissions from underground, surface, and post-mining operations is as follows:

$$\textit{Fugitive } CH_4 \textit{ Emissions} = (\textit{Annual Hard Coal Production} \times EF_{HARD\ COAL}) + (\textit{Annual Soft Coal Production} \times EF_{SOFT\ COAL})$$

Unless otherwise noted, EPA assumed that hard coal is produced in underground coal mines and soft coal is produced in surface 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.

Historical Emissions

Historical emission estimates were based on available country-reported data obtained from the UNFCCC flexible query system from 1990 through 2009 (UNFCCC, 2012). The full time series was available for most A1 countries; however, gaps existed in the time series for many of the NA1 countries. The time series was completed by applying growth rates as follows:

- EPA forecasted and backcasted reported estimates using production growth rates calculated from EIA's International Energy Statistics Portal (EIA, 2010). This method was used when two years were reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), as well as when a year requiring an estimate (e.g., 1990) occurred outside the reported years (e.g.1993-1997).
- If EIA data were not available to calculate growth rates for countries with some UNFCCC reported data, EPA calculated estimates in non-reported years using linear interpolation/extrapolation.

When UNFCCC flexible query data were not available for any years, EPA calculated historical emissions using the Tier 1 equation above, and activity data and emission factors as outlined below.

Activity Data

- EPA used coal production estimates for total primary production, hard coal production, and lignite production for 1990-2008 from EIA's International Energy Statistics Portal (EIA, 2010).
- EPA disaggregated production into above-ground mines and underground mines, assuming that hard coal is produced in underground mines, and lignite, or soft coal, is produced in aboveground mines.
- Where 2005 estimates[1] were calculated by EPA, EPA accounted for coal mine CH_4 recovery projects by adjusting the estimates to account for CH_4 abatement at projects reported in the EPA International Coal Mine Methane Projects Database (U.S. EPA 2010). Note that some *country-reported* estimates may already account for recovery projects. However, EPA does not know which country-reported estimates account for CH_4 recovery, and did not adjust 2005 country-reported estimates to account for CH_4 recovery.
- If historical data were unavailable for a particular country through the UNFCCC flexible query system or EIA's International Energy Statistics Portal, EPA assumed that coal mining emissions were zero.

Emission Factors and Emissions

- Where IPCC Tier 1 methodology was used, EPA determined CH_4 emissions from coal mining activities 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 IPCC guidelines provide low, average, and high tier 1 emission factors. The average emission factors were used for underground and surf.

[1] 2005 is the first year for which EPA has estimates on abatement from coal mine CH_4 projects.

Projected Emissions

EPA estimated future emissions by adjusting historical emissions based on the projected changes in coal production in each country's region.

EPA estimated CH_4 abated by coal mine CH_4 projects starting in 2005. Since historical estimates were used to develop future estimates, EPA did not adjust emission estimates for any country that self-reported estimates in 2005. Rather, it is assumed that countries that self-reported estimates had the opportunity to account for coal mine CH_4 projects in their own estimates, and that any country-made adjustment for coal mine CH_4 projects is captured when projecting emissions forward. For countries that did *not* self-report estimates in 2005, EPA adjusted estimates to account for CH_4 abatement due to coal mine CH_4 projects. Based on these criteria, EPA adjusted estimates for three countries: China, Mexico, and South Africa.

Activity Data

- EPA projected emissions by adjusting historical estimates based on projected changes in country coal production from EIA's International Energy Outlook (EIA, 2009). If EIA did not report country-specific coal production forecasts, EPA used EIA's estimates for the country's region. In some cases, EIA provided estimates for a few countries within a region, and then an estimate for the "rest of" the region. Where appropriate, EPA used these "rest of" estimates of forecasted coal production.
- Estimates for abated CH_4 for 2010 and 2015 were developed using information from EPA's Coal Mine Methane Projects database (U.S. EPA, 2010). EPA then estimated post-2015 abatement by assuming that the percentage of a country's coal mine CH_4 emissions that is abated remains constant starting in 2015.

Uncertainties

EPA used several methodologies to calculate historical emissions, depending on data availability for a given country. While this approach allowed EPA to develop 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 mining 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 *emissions* rather than calculating emissions based on *production* using the Tier 1 equation. This approach introduces uncertainty as it would not capture any shift in surface to underground mining (or vice versa), which are associated with different emission factors.

Finally, EPA did not adjust estimates for countries who self-reported estimates in 2005, the first year for which EPA has information on coal mine CH_4 projects. It is assumed that countries had the opportunity to incorporate abatement from CH_4 projects into their self-reported estimates; however, whether countries actually accounted for coal mine CH_4 projects in their estimates is unknown. In addition, for countries whose estimates EPA *did* adjust for coal mine CH_4 projects, EPA assumed that the percentage of a country's emissions abated by these projects remained constant starting in 2015; the extent that this assumption will hold true in the future is an additional source of uncertainty in emissions.

Table B-3 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.1.3 Stationary and Mobile Combustion (CH_4, N_2O)

If historical N_2O and CH_4 emissions data were not available or the data were insufficient, EPA developed emissions using fuel consumption data from the International Energy Agency's (IEA) Energy Balances (IEA, 2009a; IEA, 2009b) and the IPCC Tier 1 methodology. If projections were not available, EPA developed projections by applying projected growth rates of energy consumption from IEA's World Energy Outlook (WEO) (IEA, 2009c) to historical emission estimates.

The basic equations to estimate emissions from mobile and stationary sources are as follows:

$$CH_4\ Emissions = Annual\ Fuel\ Consumption\ (by\ sector\ and\ fuel\ type) \times Emission\ Factor\ (by\ sector\ and\ fuel\ type)$$

$$N_2O\ Emissions = Annual\ Fuel\ Consumption\ (by\ sector\ and\ fuel\ type) \times Emission\ Factor\ (by\ sector\ and\ fuel\ type)$$

For mobile sources, emission factors varied by the different transportation modes such as aviation, road, railway, and navigation. The main driver for determining N_2O and CH_4 emissions from stationary and mobile sources is fuel consumption, assuming that the emission factors do not change over time.

Table 7-1 presents the IEA- and IPCC-defined sectors and modes that constitute stationary and mobile combustion. Table 7-1 shows how the IEA categories fit into the IPCC-defined sectors.

Table 7-1: IEA- and IPCC-Defined Sectors and Modes for Stationary and Mobile Combustion

IEA-Defined Sectors	IPCC-Defined Sectors
1. Energy Industries[a]	1. Energy Industries
2. Total Industry Sector	2. Manufacturing Industries and Construction
3. Total Transport Sector	3. Transport
- International Civil Aviation	*(not used, bunker fuels)*
- Domestic Air Transport	- Aviation
- Road	- Road
- Rail	- Railways
- Pipeline Transport	*(used EF for Manufacturing Industries and Construction)*
- Internal Navigation	- Navigation
- Non-specified Transport	*(assumptions depends on fuel type)*
4. Total Other Sectors	4. Total Other Sectors
- Agriculture	- Agriculture/Forestry/Fishing
- Commercial and Public Services	- Commercial/Institutional
- Residential	- Residential
- Non-specified Other	*(used EF for residential or agriculture)*

[a] This sector comprises an aggregate of categories assumed to consume fuel primarily for the generation of heat and power. This determination was made after consultation with both IEA and ICF energy experts. The following

categories are included: electricity plants, combined heat and power (CHP) plants, and heat plants, and own use. Plants primarily selling to the public and primarily operating for on-site use (autoproducers) of each of these types are included.

Historical Emissions

Historical estimates were based on emissions data obtained from the UNFCCC flexible query system where data are available from 1990 through 2009 (UNFCCC, 2012). The time series was available for most A1 countries, however there are gaps in the time series for the majority of the NA1 countries. The remainder of the historical time series is based on applying growth rates to this base year estimate as follows:

- When two years are reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), EPA interpolated the missing estimate (1995) using reported estimates.
- EPA backcast or forecast emission estimates to complete the historical series for 1990, 1995 and 2000, and 2005 based on Tier 1 growth rates. This involves estimating emissions for 1990, 1995, 2000, and 2005 using a Tier 1 approach, then using the rate of growth of this emission estimate to backcast and forecast.

If the historical time series of emissions was incomplete, EPA used calculated Tier 1 annual growth rates for energy consumption from IEA's Energy Balances (IEA, 2009a; IEA, 2009b) to backcast and forecast emissions to the missing years.

If historical emission estimates were not available, EPA estimated emissions for a country and/or region using the IPCC Tier 1 methodology. This methodology allows for an estimate of emissions by sector and primary fuel type. The inputs used to estimate emissions are discussed in the following sections.

Activity Data

Fossil fuel consumption data by country, fuel product, and sector were collected from IEA's Energy Balances for all major fuel types (IEA, 2009a; IEA, 2009b). The sectors included in the analysis are listed in Table 7-1. The main fuel categories include coal, oil, and natural gas (see Table 7-2 for a listing of product categories). Biomass combustion emissions were not included in these calculations as they are included in the *Biomass Combustion* chapter, and discussed in methodology Section 7.1.4.

Table 7-2: Fuel Types Included Under Main Fossil Fuel Categories

Coal	Natural Gas	Oil
Hard Coal	Natural Gas	Crude
Brown Coal	Refinery Gas (in metric tons)	Motor Gasoline
Coke Oven Coke	Ethane	Aviation Gasoline
Gas Coke	Liquefied Petroleum Gases	Gasoline – Type Jet Fuel
Peat	Gas Works Gas	Kerosene – Type Jet Fuel
Brown Coal/Peat Briquettes (BKB)	Coke Oven Gas	Kerosene
	Blast Furnace Gas	Gas/Diesel Oil
	Oxygen Steel Furnace Gas	Residual Fuel Oil
		Petroleum Coke
		Non-specified Petroleum Products

	Naphtha
	Patent Fuel

Source: IEA, 2009a; IEA, 2009b

Emission Factors and Emissions

- To calculate emissions, EPA multiplied the IEA fuel consumption data by the IPCC Tier 1 N_2O and CH_4 uncontrolled emission factors for each fuel type and sector from IPCC, 2006.

Projected Emissions

- EPA projected emissions based on forecasts of coal, oil, and natural gas consumption for each region/country, by sector, provided by IEA WEO (IEA, 2009c).[2] Use of IEA WEO data assumes that countries within the same region have the same growth rate. EPA applied the forecasted annual growth rate of fuel consumption to emissions, based on the following scenarios:

  For 2010, 2015, 2020, 2025, and 2030: EPA forecasted emissions using the 2007-2030 annual growth rate for energy consumption for the appropriate region, by sector and fuel type.

Table B-4 and Table B-5 present historical and projected emissions for all countries for this source. Appendix G and Appendix H describe the methodologies and data sources used for each country.

Uncertainties

A high degree of uncertainty is associated with the IPCC Tier 1 default emission factors used to calculate emissions from both stationary and mobile combustion. For stationary combustion sources, this high degree of uncertainty is a result of lack of relevant measurements, uncertainties in measurements, or an insufficient understanding of the emission generating process (IPCC, 2006). The 2006 IPCC Good Practice Guidance estimates uncertainty for the stationary CH_4 combustion emission factors at ±50 to 150 percent. Uncertainty for stationary combustion N_2O 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 N_2O and CH_4 emission factors for mobile combustion are relatively high and depend 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, 2006).

Higher certainty is associated with the aggregate fuel consumption data on which estimates are based, due to established statistical approaches and surveys used to collect IEA data. Estimates of uncertainty for fossil fuel consumption data can range from ±1 to 10 percent depending on the collection method used to acquire activity data (IPCC, 2006).

[2] The regions and countries are: Transition Countries, Russia, China, South Asia, India, East Asia, Latin America, Brazil, Africa, and the Middle East.

Table B-4 and Table B-5 present historical and projected emissions for all countries for this source. Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.1.4 Biomass Combustion (CH_4, N_2O)

The basic equation to estimate emissions from biomass combustion is as follows:

$$Emissions = Emission\ Factor * Activity$$

Where:

- The emission factor is specific to each fuel type (solid biomass, charcoal, liquid biomass, other) and sector (such as energy industries and manufacturing).
- The activity is the energy input in terajoules (TJ) or metric tons of fuel.

Historical Emissions

Historical estimates were based on emissions data obtained from the UNFCCC flexible query system where data were available from 1990 through 2009 (UNFCCC, 2012). The time series was available for most A1 countries, however there are gaps in the time series for the majority of the NA1 countries. The remainder of the historical time series is based on applying growth rates to this base year estimate as follows:

- When two years were reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), EPA interpolated the missing estimate (1995) using reported estimates.
- EPA applied regional (or country-specific when available) annual growth rates to the emission estimates to complete the historical time series of emissions. Compound growth rates are directly from Annex A of the International Energy Agency's (IEA) World Energy Outlook, Biomass and Waste category (IEA, 2009c), for 2007 through 2030.

Activity Data

- EPA established historical energy demand for each country, using 1990, 1995, 2000, 2005, and 2007 consumption data from the IEA Energy Statistics for OECD and non-OECD countries (IEA 2009a, IEA 2009b). Consumption data are presented for the following sectors and subsectors: total solid biomass composed of industry (energy and manufacturing), and transportation; other (which is composed of residential, commercial, agricultural, and unspecified other); liquid biomass; charcoal; and industrial waste.
- EPA forecasts 2007 emissions by applying annual growth rates from Annex A of IEA's World Energy Outlook (IEA, 2009c) Biomass and Waste category through 2030. EPA applied country-specific growth rates when they were available through the World Energy Outlook (WEO); otherwise the regional growth rates were applied to the 2007 estimate. In projecting consumption, the distribution of energy supplied by biomass into the relevant subsector is assumed to remain constant.

Emission Factors and Emissions

- EPA determined CH_4 and N_2O emissions from biomass combustion by multiplying activity data (i.e., biomass fuel consumption by sector for each country) by uncontrolled, default Tier 1 IPCC emission factors from IPCC, 2006.

Projected Emissions

Activity Data

- EPA used 2007 as base year to project biomass fuel consumption in 2010, 2015, 2020, 2025, and 2030. Annual growth rates are directly from Annex A of IEA, 2009c, Biomass and Waste category, through 2030.

Emission Factors and Emissions

- The emission factors used to calculate projected emissions are the same IPCC default factors used in the historical time series calculations.

Uncertainties

Emission factors for biomass fuel are not as well developed as those for fossil fuels due to 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 CH_4 and N_2O factors (± 50 to 150 percent).

Activity data for biomass fuel combustion also tends to be much more uncertain than fossil fuels due to the smaller, dispersed and localized collection and use of these fuels, which makes tracking consumption more difficult. Estimates in IPCC Good Practice Guidance suggest uncertainties in the range of ±10 to 100 percent.

Table B-6 and Table B-7 present historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.1.5 Other Energy Sources (CH_4, N_2O)

Emission estimates for the "Other Energy Sources" emissions category are based on UNFCCC-reported data. Projected emissions from this source are assumed to remain constant at the value for the last reported year. Similarly, values before the first reported year are assumed to equal that year's value and values between two reported values are calculated using a linear interpolation. Emissions were not estimated for countries that did not report emissions in any year. As a result, estimates are mostly available only for Annex I countries.

Table B-8 and Table B-9 present historical and projected emissions for all countries for this source. Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.2 Industrial Processes

7.2.1 Adipic Acid and Nitric Acid Production (N_2O)

Estimates for N_2O emissions from adipic and nitric acid production rely first on country-reported emissions data. Where gaps exist in country-reported historical estimates and/or projections, EPA used the IPCC Tier 1 methodology to estimate emissions in order to develop annual growth rates, which are then applied to reported data in order to complete the historical and projected time series (IPCC, 2006).

The basic Tier 1 equation used to estimate emissions from adipic acid production is as follows:

$$N_2O \text{ emissions} = \text{Adipic Acid Production} * \text{Unabated Emission Factor}$$

The basic Tier 1 equation used to estimate emissions from nitric acid production is as follows:

$$N_2O \text{ emissions} = \text{Nitric Acid Production} * \text{Unabated Emission Factor}$$

Historical Emissions – Adipic Acid Production

Activity Data

- Where country-reported emissions data were unavailable, production data were estimated based on adipic acid plant capacity figures and estimated capacity utilization. Capacity utilization was assumed to be 75 percent in 1990, 80 percent in 1995, 90 percent in 2000 and 2005, and 82 percent in 2010 through 2030 (SRI, 2010; Chemical Week, 2007, 1999).

Emission Factors and Emissions

- The IPCC uncontrolled default emission factor for N_2O generation is 300 kilograms N_2O per metric ton adipic acid (IPCC, 2006). This factor is applied to all countries where Tier 1 calculations are used.

Projected Emissions – Adipic Acid Production

Activity Data

- Global adipic acid consumption was forecasted to increase by 3.5 percent annually for the period 2008 through 2013 (SRI, 2010). In this analysis, projections of global adipic acid consumption are used as a surrogate for production projections, and the 3.5 percent growth rate is applied through 2030.

Emission Factors

- Emission factors used for projections are the same as those used in historical time series calculations.

Historical Emissions – Nitric Acid Production

Activity Data

- Production data are estimated by apportioning global nitric acid production to the country level using country-specific fertilizer consumption data (FAO, 2010; SRI, 2007, 1999).

Emission Factors and Emissions

- The unabated emission factor used for Tier 1 calculations is 9 kilograms N_2O per metric ton nitric acid (IPCC, 2006).

Projected Emissions – Nitric Acid Production

Activity Data

- Emissions from nitric acid production are projected based on changes in estimated long-term fertilizer consumption (Tenkorang & Lowenberg-DeBoer, 2008) as discussed in the agricultural soils section (see Section 7.2.6).

Emission Factors

- Emission factors used for projections are the same as those used in the historical time series calculations.

Uncertainties

In general, IPCC default adipic acid emission factors are more certain than nitric acid emission factors because they are 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 percent. The uncertainty range given for the unabated nitric acid emission factor is ±40 percent. 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. Regarding activity data, estimates of nitric acid production derived in part from national fertilizer consumption are much more uncertain than reported estimates. While estimates of nitric acid production described above are used to inform the trend in actual nitric acid production, they may not reflect true annual production.

Table C-2 presents historical and projected emissions for all countries for this source. Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.2.2 Use of Substitutes for Ozone Depleting Substances (HFCs)

EPA used a modeling approach to determine emissions from the various ODS substitute end-use sectors (refrigeration/air-conditioning, foams, aerosols, fire extinguishing, and solvents). Although some nations have made significant efforts to track and project use and emissions of HFCs from ODS substitutes, the methodologies used, scope covered, and the level of aggregation presented have varied and so are not used in this report. To estimate emissions, EPA modeled HFC emissions based upon reported ODS consumption data. Nations that have ratified the Montreal Protocol are required to report ODS consumption by chemical "group" (e.g., CFCs) to the United Nations Environmental Programme (UNEP) Ozone Secretariat; and as of this report, 196 nations had ratified the Montreal Protocol.

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 disposals. Some consumption may be recovered or recycled, depending upon the end use and country. The relationship between initial consumption and eventual emission is complex and uncertain. Comparing modeled emission estimates to atmospheric measurements is beyond the scope of this report.

First, EPA used a bottom-up "Vintaging Model" (EPA, 2010) of ODS- and ODS-substitute-containing equipment and products to estimate the use and subsequent emissions of ODS substitutes in the U.S. Emissions from non-U.S. countries were then estimated for each ODS-consuming sector. In developing these estimates, EPA initially assumed that the transition from ODSs to HFCs follows the same substitution patterns as the U.S. 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. This methodology is described in more detail in the following sections.

Estimating ODS Substitute Emissions in the U.S.

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 U.S. 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). The model and the equations used to estimate emissions are discussed in more detail in Appendix K.[3]

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 emissions profile (e.g., annual leak rates, service emission rates, and disposal emission rates for air conditioning and refrigeration end-uses) to each 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 60 different end uses.

For this analysis, the model calculated a "business-as-usual" (BAU) case that does not incorporate measures to reduce or eliminate the future emissions of these gases, other than those regulated by U.S. law or otherwise largely practiced in the current market. 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.

The major end-use sectors defined in the Vintaging Model for characterizing ODS use in the U.S. are refrigeration and air-conditioning, aerosols (including metered-dose inhalers (MDI)), 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 emissions 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 are 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.

Estimating ODS Substitute Emissions in Other Countries

After U.S. emissions are calculated using the Vintaging Model, EPA developed emission estimates for non-U.S. countries by building on the detailed U.S. assessment. The general methodology and assumptions used by EPA are discussed below, although the methodology was modified for several sectors where necessary. Specific deviations from this basic methodology are discussed following the general methodology description.

[3] A discussion of the Vintaging Model can also be found in the U.S. Inventory of Greenhouse Gas Emissions and Sinks (EPA, 2010).

General Methodology

The following general steps are applied to estimate country-specific emissions. Steps 1 through 7 results in preliminary emission estimates calculated by Equation 1, below. The preliminary estimates were adjusted based on a series of factors discussed in Steps 8 through 11.

1. *Gather base ODS consumption data for each country.* UNEP (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; when data for 1989 was unavailable, the earliest available data was used as a proxy because, in general, ODS substitution had not yet taken place. Since data was only available in ODP-weighted totals by ODS "group", groups were divided into component chemicals (e.g., CFC-11, CFC-12, etc) 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 percent of base ODS consumption of each chemical group used in each end-use sector.* The amount of ODS use in various industrial sectors differs by country. Data on the end-use distributions of ODS in 1990 were available for the following countries:

   - U.S. from the Vintaging Model,
   - United Kingdom (U.K.) from *U.K. Use and Emissions of Selected Halocarbons*, prepared for the Department of the Environment (March, 1996), and
   - 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 U.S. was applied to Canada and Japan. The U.K.'s distribution was applied to the EU-15[4], non-EU Western Europe[5], Australia, and New Zealand. Russia's distribution was applied to the Former Soviet Union and Eastern European countries. For developing countries, data on the 1990 consumption of ODS were available for many nations[6] by sector and substance from the Multilateral Secretariat. For developing countries that did not have data available, EPA used a representative average.

[4] The EU-15 is defined as these European Union (EU) members: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

[5] Iceland, Liechtenstein, Monaco, Montenegro, Norway, and Switzerland.

[6] 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, Zimbabwe.

3. *Calculate the base consumption of ODS 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.

5. *Estimate HFC consumption in metric tons.* This step involves multiplying the country-specific base level consumption of ODS (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 CO_2 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 2012 in the U.S., as obtained from the Vintaging Model. The year 2012 is used as a representative average; the U.S. HFC market is assumed to be mature by this date and, under a business-as-usual 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.

Equation 1:

$$\underset{[\text{country, year}]}{\text{HFC Emissions } (MtCO_2e)} = \underset{\substack{[\text{country, 1989 or as available}] \\ \text{Step 3}}}{\text{ODS Consumption } (MT)} \times \frac{\text{HFC Consumption } (MT)\ [\text{U.S., year}]}{\underset{[\text{U.S., 1989}]}{\text{ODS Consumption } (MT)}} \times \frac{\text{HFC Emissions } (MT)\ [\text{U.S., year}]}{\underset{[\text{U.S., year}]}{\text{HFC Consumption } (MT)}} \times \underset{[\text{U.S., 2012}]}{\text{Average GWP of HFC Emissions } (MtCO_2e/MT)}$$

Step 5 Step 6 Step 7

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 ODS in a similar manner as the U.S. (For example, CFC-12 mobile air conditioners transitioned to HFC-134a beginning in 1994 in the U.S. Thus, as a first estimation, it is 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 U.S. are available and in many cases

are used worldwide. These assumptions may be adjusted in later steps to account for differences between the U.S. and other countries, as explained below.

8. *Develop and apply adjustment factors.* In this analysis 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 U.S. For example, EPA multiplied the estimates produced in step 7 by adjustment factors of less than one to refrigeration and air-conditioning end-uses, because some nations have been more likely to use hydrocarbon refrigerants than HFCs and/or because some nations may choose less emissive designs or practices. Table 7-3 shows the adjustment factors used for each sector and country grouping.

Table 7-3: Adjustment Factors Applied in Each Sector/Country

	Ref/AC	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
European Union	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

9. *Develop timing factors.* Since most developing countries will transition to substitutes more slowly, 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[7]. Timing factors for CFCs start at 25 percent in 1995 and increase by 25 percent at each 5-year interval, until they reach 100 percent in 2010, 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 7-4.

Table 7-4: Timing Factors Used For Developing (Article 5) Countries

	1995	2000	2005	2010	2015	2020	2025	2030
CFCs	0.25	0.50	0.75	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

10. *Develop economic growth factors.* Since other countries' economies are growing at different rates than the U.S., EPA altered emissions based on comparisons between U.S. and regional historical and projected GDP. These GDP growth factors are shown in Table 7-5 (USDA, 2009).

[7] A complete list of Article 5 countries is available at http://ozone.unep.org/Ratification_status/list_of_article_5_parties.shtm.

Table 7-5: GDP Growth Factors (Relative to U.S.)

Region	1995	2000	2005	2010	2015	2020	2025	2030
Africa	0.91	0.87	0.96	1.11	1.23	1.36	1.49	1.61
Asia	1.24	1.17	1.31	1.49	1.66	1.85	2.03	2.22
Australia/New Zealand	1.04	1.02	1.07	1.11	1.14	1.16	1.18	1.19
Brazil	1.03	0.93	0.95	1.07	1.15	1.22	1.30	1.38
Canada	0.96	0.97	0.98	0.97	1.02	1.02	1.02	1.02
Central/South America	1.09	1.00	1.04	1.21	1.28	1.37	1.46	1.55
China	1.58	1.95	2.75	4.11	5.32	6.68	8.40	10.51
Eastern Europe	0.87	0.83	0.90	0.98	1.04	1.10	1.15	1.19
Economies in Transition	0.55	0.49	0.59	0.64	0.71	0.80	0.89	0.99
EU	0.95	0.90	0.87	0.84	0.80	0.76	0.72	0.68
Europe (non-EU)	0.95	0.90	0.87	0.84	0.80	0.76	0.72	0.68
India	1.14	1.24	1.52	2.06	2.61	3.24	3.94	4.77
Japan	0.95	0.82	0.78	0.72	0.69	0.66	0.64	0.62
Mexico	0.95	1.02	0.99	0.99	1.03	1.08	1.14	1.19
Middle East	1.04	1.02	1.13	1.25	1.37	1.49	1.63	1.76
South Korea	1.29	1.31	1.46	1.54	1.66	1.79	1.92	2.06

11. *Estimate adjusted HFC emissions in metric tons of CO_2 equivalent in a given year by country.* 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 factor (Step 10).

Sector-Specific Adjustments to General Methodology for ODS Substitutes

In addition to the adjustments discussed above, 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.

Fire-Extinguishing

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, EPA adjusted emissions in the EU to account for the rapid halon phase-out due to regulation. Details of these adjustments include the following:

1. 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 U.K. was obtained from Halon Technical Options Committee (HTOC) members from those countries.[8] Information for the U.S. was taken from the Vintaging Model. General information was also collected on Northern, Southern, and

[8] 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.

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 assumes that all halon systems in the EU-15 will be decommissioned by 2004. No adjustments were made to the 10 countries that joined the EU in May 2004, because the regulation makes exceptions for these countries.

Refrigeration and Air-Conditioning

EPA adjusted estimates for the refrigeration and air-conditioning sector to account for less refrigerant recovery (i.e., more venting) in developing countries. These estimates assume that recovery does not occur in these countries in any small refrigeration and air-conditioning units, but does occur in larger units, such as chillers. The resulting adjustment factors are shown in Table 7-6.

Table 7-6: Recycling Adjustment Factors Applied to Refrigeration Emission Estimates

1995	2000	2005	2010	2015	2020	2025	2030
1.00	1.02	1.06	1.09	1.09	1.09	1.22	1.26

Aerosols

Since the ban on CFC use in MDI aerosols caused the U.S. to transition out of CFCs earlier than other countries, the U.S. consumption of ODS in 1990 for non-MDI aerosols is assumed to be equal to zero. In order to determine a non-zero denominator for the ratio calculated in step 4, it was assumed that 15 percent of the non-MDI aerosols ODS consumption transitioned to HFCs, while the remainder was assumed to transition to not-in-kind (NIK) or hydrocarbon 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 (CEITs), and China. It was assumed that other non-Annex I 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 to the U.S. (step 9 above).

Table C-3 presents historical and projected emissions for all countries for ODS substitutes in each sector: aerosols (MDI), aerosols (non-MDI), fire-extinguishing, foams, refrigeration and air conditioning, and solvents.

7.2.3 HCFC-22 Production (HFCs)

Trifluoromethane (HFC-23) is generated and emitted as a byproduct during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used, primarily, as a feedstock for production of synthetic polymers and, secondarily, in emissive applications (primarily air conditioning and refrigeration). Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out under the Montreal Protocol. However, feedstock production is permitted to continue indefinitely.

All producers in developed countries have implemented process optimization and/or thermal destruction to reduce HFC-23 emissions. In a few cases, HFC-23 is collected and used as a substitute for ozone-depleting substances, mainly in very-low temperature refrigeration and air conditioning systems. Emissions from this use are quantified under air conditioning and refrigeration and are therefore not included here. HFC-23 exhibits the highest global warming potential of the HFCs, 11,700 under a 100-year time horizon, with an atmospheric lifetime of 264 years.

Estimating Historical HFC-23 Emissions

EPA estimated historical HCFC-22 production and used an emission rate to estimate the HFC-23 emissions, subtracting any emissions that were abated through technology. Country-specific HCFC production data as reported to the United Nations Environmental Program (UNEP) Ozone Secretariat (UNEP 2010); 2001, 2004, and 2007 country-specific production capacity information from the Chemical and Economics Handbook (CEH) (CEH 2001; Will et al., 2004; Will et al., 2008); and field data on HFC-23 emissions from HCFC-22 production (Montzka et al., 2010) were used to estimate historical HFC-23 emissions from HCFC-22 production. HFC-23 emissions were estimated to occur from a total of 20 countries that produce HCFC-22, and of this total, only 12 are are assumed to continue to produce HCFC-22 through 2030.

Countries that produce HCFC-22:
1) Argentina;
2) China;
3) Germany;
4) India;
5) Japan;
6) Mexico;
7) Netherlands;
8) Russian Federation;
9) South Korea;
10) Spain;
11) United States; and
12) Venezuela.

Countries with historic HCFC-22 production only:
1) Australia;
2) Brazil;
3) Canada;
4) France;
5) Greece;
6) Italy;
7) South Africa; and
8) United Kingdom.

Activity Data

Estimating Production in Europe

Information on historical HCFC-22 production was used to estimate HFC-23 emissions. According to Will et al. (2004), Greece's, the Netherlands', and Spain's HCFC production is only HCFC-22 (based on plant capacities). UNEP (2010) reports total non-feedstock HCFC production by country in ODP-weighted tons. As a result, non-feedstock HCFC-22 production for these countries is assumed to be the total reported for each country in UNEP (2010) after "un-weighting" the production estimates by HCFC-22's ODP (0.055). The ratio of non-feedstock production to feedstock production is then used to grow non-feedstock HCFC-22 production to total HCFC-22 production, without exceeding the CEH (2001) and Will et al. (2004) reported production capacities. The ratio of non-feedstock production to feedstock production as shown in Table 7-7 was estimated over the time series based on data for 1990 from EPA (2006), data for 1996 and 2007 from Montzka et al. (2010), and by linearly interpolating the intervening years.

This total is subtracted off Will et al. (2004) reported Western Europe production across the time series and the remaining HCFC-22 production for Western Europe is allocated to France, Germany, Italy, and the United Kingdom based on total HCFC-22 production capacity for each country as reported in CEH (2001, 2008) and Will et al. (2004). EPA assumed that for all European countries, production from 1990 through 2003 could not exceed 2001 reported capacity, that production in 2004 through 2006 could not exceed 2004 reported capacity, and that production in 2007 could not exceed 2007 reported capacity.

Table 7-7: Portion of Total HCFC-22 Production that is Feedstock HCFC-22 Production for Annex I (A1) countries

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
A1	20%	26%	28%	31%	33%	36%	39%	41%	44%	47%	50%	52%	55%	58%

Estimating Production in the Rest of the World

According to Will et al. (2004) Mexico's, Argentina's, Venezuela's and India's HCFC production is also only HCFC-22 (based on plant capacities). Again, UNEP (2010) reported HCFC production is assumed to be the total non-feedstock HCFC-22 production reported for each country by "un-weighting" the production estimates by dividing the total production by HCFC-22's ODP of 0.055.

For South Korea, 33 percent of total HCFC production capacity is HCFC-22 (Will et al. 2004, 2008). This percent is applied across the UNEP-reported non-feedstock HCFC production time series to estimate non-feedstock HCFC-22 production totals. The ratio of non-feedstock production to feedstock production is then used to grow non-feedstock HCFC-22 production to total HCFC-22 production.

Will et al. (2008) reports China's apparent production for 2000 through 2007. EPA used these estimates and back casted HCFC-22 production using the ratio of total HCFC-22 production reported in Will et al. (2008) to UNEP-reported non-feedstock HCFC production for 2000. This ratio was applied across the UNEP-reported time series for 1990 to 1999 to estimate China's HCFC-22 production for those years. The ratio of non-feedstock production to feedstock production across the time series for China and other non-Annex I countries and Russia is shown in Table 7-8 below.

Table 7-8: Portion of Total HCFC-22 Production that is Feedstock HCFC-22 Production for Non-Annex I (NA1) Countries

	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
NA1	20%	31%	33%	32%	31%	30%	29%	28%	27%	26%	26%	25%	24%	23%

Historical Emissions Calculation

To estimate emissions of HFC-23, the HCFC-22 production levels estimated above were multiplied by emission rates (i.e., tons of HFC-23 emitted per ton of HCFC-22 produced). In some cases the emission estimate was reduced due to assumed market penetrations of thermal abatement technologies. The emission rate for Annex I countries was assumed to be 2 percent across the entire time series (Montzka et al., 2010). The emission rate for non-Annex I countries and Russia was assumed to be 3 percent from 1990 through 2005 (EPA, 2006) and 2.9 percent from 2006 through 2007 (Miller et al., 2010). The decreased emission rate takes into account any HFC-23 emission offsets from Clean Development Mechanism (CDM) projects in these countries and the Joint Implementation (JI) project at Russia's HCFC-22 plant in Perm.

To reflect the adoption of thermal oxidation technology between 1995 and the present, EPA assumed that current emission rates had been reduced 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 percent in Germany and Italy, and 75 percent in the U.K (Harnisch and Hendriks, 2000). Except for the U.K., these levels were assumed to be maintained through 2030.
- In 2005, the baseline market penetration of thermal oxidation in the U.K. was estimated to be 87.5 percent. 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 percent. No emissions were estimated for the U.K. after 2008 as a result of their two HCFC-22 plants closing during the course of 2008 (MacCarthy et al., 2010)

Where UNFCCC-reported HFC-23 emission estimates were available, these estimates were used in place of estimates calculated using production data (UNFCCC, 2012). Countries for which UNFCCC historical emission estimates (1990 through 2007) were used are: France, Greece, the Netherlands, Russia, Spain, and the United States; partial time series emission estimates from the UNFCCC were available for Australia (1990), Canada (1990 and 1995), Italy (1990 and 1995), Japan (1995 through 2007), and Brazil (1990).

Estimating Projected HFC-23 Emissions

Activity Data

HFC-23 emission projections were developed for Annex I countries including Germany, Japan, the Netherlands, Russia, Spain, and the United States. For the United States, National Communications projections of emissions were used for 2010-2020 (UNFCCC, 2009); emissions trends were used to project HFC-23 emissions for the remainder of the time series (2025 through 2030).

For all other Annex I countries, the dispersive production and feedstock production portion of emissions were projected separately to account for the decline in the production for dispersive

purposes because of the phaseout requirements of the Montreal Protocol. The following assumptions for these countreis were applied to estimate dispersive production:

- For Australia and Canada, UNFCCC reported emissions of HFC-23 were zero beginning in 2000 and 1995, respectively. No further data was available on Australia, so EPA assumed Australia will not produce HCFC-22 in the future. Will et al. (2004) reports that Canada only produces one HCFC, HCFC-123, so EPA assumed that Canada will not produce HCFC-22 in the future.
- For the U.K., France, and Italy; HCFC-22 production was assumed to end and therefore emissions were set equal to zero.
- For developed countries other than Australia, Canada, the U.K., France, and Italy, emissions from non-feedstock production were assumed to decrease linearly from 2007 so that no emissions resulted from HCFC-22 non-feedstock production by the 2020 phaseout date under the Montreal Protocol.

To project the feedstock production portion of HFC-23 emissions, EPA applied the 5 percent global growth rate of feedstock HCFC-22 production as reported in Montzka et al. (2010) for all countries.

HFC-23 emission projections were developed for non-Annex I countries including China, India, Mexico, South Korea, and Venezuela. To do so, non-Annex I aggregate HCFC-22 production was projected for both dispersive and feedstock production.

- **HCFC-22 dispersive production** for developing countries was projected using a 2010 HCFC-22 production estimate of 395 (1,000 MT), as provided by Miller et al. (2011), and a baseline estimate of 383 (1,000 MT) and the percent reductions from that baseline as prescribed by the accelerated phaseout schedule of the Montreal Protocol.
- **HCFC-22 feedstock production** was projected for developing countries by extrapolating from the 2008 estimate of developing countries HCFC-22 feedstock production as reported by Miller et al. 2010.

Production was then disaggregated by country using the percent of each country's contribution to 2007 non-Annex I 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 are facilities that have abatement controls in place already. 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 and Venezuela.
- **New Uncontrolled Facility:** New facilities are assumed to be uncontrolled when built. It is assumed that a new facility enters the market once projected production exceeds current capacity. In other words, the percentage of emissions from new facilities is 0% until projected production exceeds capacity.

- **Post-CDM Facility:** Similar to the "less mitigation scenario of Miller et al. (2011), this analysis assumes that the 12 CDM projects that opted for a 7-year crediting period (in China, South Korea, Mexico, and Argentina) are not renewed after their first terms (note the remaining seven facilities opted for a one-time fixed crediting period that cannot exceed 10 years). Under this assumption, by 2020, all facilities previously controlled via CDM ("residual emission model facility") are considered a "post-CDM" facility. It is assumed that the incineration device installed (via a CDM project) will not be kept in operation once the CDM crediting period is over.

HFC-23 emissions were then projected using two HFC-23/HCFC-22 co-production ratios to develop estimates—to address the varying use of abatement technologies by facilities.

- The HFC-23/HCFC-22 co-production ratio of 2.9% (representative of the CDM's annual mean ratio for 2009) (Miller et al. 2010), was used to estimate emissions.
- For emissions associated with model facility "residual", the HFC-23/HCFC-22 co-production ratio was modified by 55% to account for a reduction efficiency associated with the incinerator. Although reduction efficiency is closer to 95% for incineration, a lower reduction efficiency takes into account startups, shutdowns, and malfunctions. This method also results in emission estimates more in line with those published by Miller et al. (2011), which relied on actual CDM abatement reporting to determine non-released HFC-23 from facilities with CDM projects.

Uncertainties and Sensitivities

In developing these emission estimates, EPA made use of, multiple international data sets, country-specific information on abatement levels (where available), and the 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. Although 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 Chemical and Economics Handbook; field data on HFC-23 emissions from HCFC-22 production; and the IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System), none of these sources is comprehensive. Specifically, none provide country-by-country production of HCFC-22 for all countries. As a result, EPA used different ratios to estimate total HCFC-22 production over time for several countries (e.g., percent 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. Changing emission rates may also have a significant impact on emissions. There is a significant probability that many of these emissions will be averted, either through CDM or other mechanisms. In this case, HFC-23 emissions will be lower than projected in this analysis. This analysis examines a scenario in which the current CDM projects, including those projects with seven-year crediting periods, are completed by 2020.[9] Whether project renewals will occur is uncertain; it is also uncertain whether facilities would continue to abate even in the absence of CDM incentives. Although, the first seven-year crediting period for the South Korean plant in Ulsan, which ended in

[9] This scenario is similar to the "Less Mitigation" scenario as presented by Miller et al (2011).

December 2009, was recently renewed for another 7 years by the CDM Executive Board in November 2011, the European Commission recommended in January 2011 that the EU cease the purchase of CERs derived from emission mitigation of HFC-23 production after May 2013 (Europa 2012). The projections in this analysis do not attempt to examine emission projections under a scenario where CDM projects are renewed post 2020.

Table C-4 presents historical and projected emissions for all countries for this source.

7.2.4 Electric Power Systems (SF_6)

Historical Emissions

Country-reported emission estimates available from the UNFCCC flexible query system (UNFCCC, 2012) were used for historical estimates. Where UNFCCC reported data were not available, EPA estimated historical global emissions using the 2004 RAND survey (Smythe, 2004) of global SF_6 sales to electric utilities and equipment manufacturers, estimates of net electricity consumption, and the following equation, which is derived from the equation for emissions in the IPCC Good Practice Guidance (IPCC, 2000): [10,11]

$$Emissions = SF_6 \text{ purchased to refill existing equipment} + \text{nameplate capacity of retiring equipment}$$ [12]

Note that the above equation holds true whether the gas from retiring equipment is released or recovered. Recovered gas is used to refill existing equipment, lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 to 2003 were available from the 2004 RAND survey (Smythe, 2004). For the SF_6 markets represented in the RAND survey (believed to include all SF_6-consuming countries except Russia and China), SF_6 purchased to refill existing equipment in a given year was assumed to be approximately equal to the SF_6 purchased by utilities in

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[10] Emission estimates based on RAND sales data do not include SF_6 emissions from electrical equipment manufacturing. However, some of the UNFCCC reported data that was used does include emissions from the manufacture of electrical equipment.

[11] Guidance from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) was not used because the methods contained in the 2006 Guidelines are not well suited to estimate global SF_6 emissions from electric power systems given the type of data available on global SF_6 use.

[12] According to the 2000 IPCC *Good Practice Guidance,* emissions from electrical equipment can be summarized by the following equation:

$$Emissions = \text{Annual Sales of } SF_6 - \text{Net Increase in nameplate } (SF_6) \text{ capacity of equipment} - SF_6 \text{ stockpiled or destroyed}$$

Where:

Annual Sales = SF_6 purchased to fill new equipment + SF_6 purchased to refill existing equipment;

Net Increase in nameplate capacity = nameplate capacity of new equipment-nameplate capacity of retiring equipment; and

SF_6 stockpiled or destroyed = SF_6 stockpiled or recovered from electrical equipment and destroyed

In general, the quantity of SF_6 destroyed is believed to be small compared to the other quantities in the equation. In addition, if no gas from retiring equipment is used to fill new equipment, then the quantity of new SF_6 used to fill new equipment is equal to the nameplate capacity of the new equipment. In this case, the IPCC equation simplifies the expression above.

that year.[13,14] To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 77.5 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 77.5 percent of the gas purchased by original equipment manufacturers (OEMs) in 1960).[15] The remaining 22.5 percent was assumed to have been emitted at the time of manufacture. The 22.5 percent emission rate is an average of IPCC SF_6 emission rates for Europe and Japan before 1996 (IPCC, 2000). The 40-year lifetime for electrical equipment is from *Reductions of SF_6 Emissions from High and Medium Voltage Electrical Equipment in Europe* (Ecofys, 2005). To reduce the potential impact of inventory fluctuations on the estimates, EPA applied three-year smoothing to both the utility and the OEM sales figures. The results of the two components of the above equation were then summed to yield estimates of total SF_6 emissions for all of the countries represented in the RAND survey from 1990 to 2003.

For 2005 historical emissions, EPA extrapolated the 2003 emission estimates based on the change in world net electricity consumption from 2003 to 2005, as provided by EIA (EIA, 2008). It was necessary to use extrapolation for 2005 emissions because RAND ceased publication of their survey in 2004, so 2003 was the last year for which RAND survey data were available.

Country-Specific Historical Emissions Methodology

United States

Historical emissions data for the United States used in this analysis were available through the UNFCCC flexible query system (UNFCCC, 2012).

EU

Emissions for the EU were based on UNFCCC reported data, where available (UNFCCC, 2012). When data were not available, emissions were based on those provided for equipment use and decommissioning in *Reductions of SF_6 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 SF_6 bank in equipment, both of which varied by region and over time. The study supplemented published information and national reporting with surveys of electrical equipment manufacturers and users.

The Ecofys report provided estimates on a regional level for 1995, 2003, 2010, and 2020. For this analysis, estimates were extrapolated or interpolated to obtain values for 1990, 2000, 2005, 2015, 2020, 2025, and 2030, and regional totals were disaggregated to the country level using either country-specific data (for Germany) or GDP (for all other countries).[16] To estimate 1990 emissions,

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[13] 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, one percent of new equipment was filled using gas purchased by utilities and that by 2003; this fraction had grown to five percent. This assumption has the effect of decreasing estimated global refills and emissions by 11 percent in 2003.

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

[15] The volume of SF_6 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.

[16] Ecofys indicated that within the three European regions, GDP was a slightly better predictor of emissions than net electricity consumption.

trends for Germany between 1990 and 1995 were applied to EU-15[17] and Norway, Switzerland, and Iceland. Emissions in 1990 from the EU-10[18] were assumed to be equal to the 1995 estimates.

Japan

Historical emissions data for the Japan used in this analysis were available through the UNFCCC flexible query system (UNFCCC, 2012).

All Other Countries

For all countries except the U.S., Japan, the EU, and nine other miscellaneous countries that had historical data reported through the UNFCCC flexible query system (UNFCCC, 2012),[19] historical emissions (1990 through 2003) from electrical equipment were estimated using world sales of SF_6 to electrical utilities and country-level net electricity consumption data (Smythe, 2004; EIA, 2008).

To estimate world sales of SF_6 that should be allocated to the "all other countries" category, emissions for the U.S., the EU, and Japan were deducted from the global SF_6 sales to electric utilities value from the RAND survey. This global SF_6 sales value first had to be adjusted to include sales for China and Russia, which were not included in the RAND survey. To make this adjustment, EPA assumed Russian and Chinese SF_6 sales were proportional to the net electricity consumption of these countries. Estimates of net electricity consumption were available from the Energy Information Administration (EIA, 2008). To obtain a global sales value that included China and Russia, the total sales for the countries represented in the RAND survey were multiplied by the ratio of total global net electricity consumption (including Russia and China) to global net electricity consumption excluding Russia and China.

The emissions for the EU and Japan that were subtracted from the RAND global sales were not the same UNFCCC reported values that are presented as estimated emissions for the EU and Japan in this report. Instead, Ecofys data was used for all the EU countries even for countries that had UNFCCC reported data and emissions for Japan were estimated from the paper *Recent Practice for Huge Reduction of SF_6 Gas Emission from GIS & GCB in Japan* (Yokota et al., 2005).

These alternative emission estimates were necessary because much of the UNFCCC reported data includes emissions from electrical equipment manufacturing, but the method for estimating emissions from RAND sales data only applies to electric utilities. To be consistent, the values deducted for EU-23+3 and Japan from the RAND global sales needed to only include emissions from electric utilities and not emissions from manufacturing. The Ecofys data as well as the Japan estimates from Yokota et al. were for electrical utilities only.

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[17] The EU-15 includes these European Union (EU) members: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom.

[18] The EU-10 includes these EU members: Poland, Hungary, Czech Republic, Slovak Republic, Lithuania, Latria, Slovenia, Estonia, Cyprus, and Malta.

[19] Other countries with UNFCCC reported historical data were Australia, Belarus, Bulgaria, Canada, Croatia, New Zealand, Romania, Russia, and Turkey.

The amount of RAND sales remaining after the deduction for the U.S., EU-25+3, and Japan were assumed to equal the total emissions from all other countries.[20] This amount was allocated to the remaining countries according to each country's share of world net electricity consumption. Country-specific electricity consumption data for the period 1990 to 2003 was obtained from the International Energy Annual 2006 (EIA, 2008).

Country-Specific Projected Emissions Methodology

Since the mid-to-late 1990s various developed countries have implemented voluntary (and in some cases, mandatory) programs aimed at reducing SF_6 emissions from electric power systems. These countries include the U.S., Japan, and the EU. The successful attainment of developed country SF_6 reduction goals are accounted for in the emission projections based on the following methodology.

United States

For the U.S., EPA assumed that emissions would decline over time as new, small, leak-tight equipment gradually replaced old, large, leaky equipment, and as many utilities implemented reduction measures under EPA's SF_6 Emissions Reduction Partnership for Electric Power Systems.[21] These assumptions are built into the U.S. emission projections provided in the U.S. Fifth National Communication and used in this analysis for the years 2010 through 2020 (U.S. State Department, 2010). Because the Fifth U.S. National Communication does not provide projections past 2020, linear regression was used to extrapolate emissions to 2030 (based on 2010 through 2020 emissions).

EU

For the EU emissions projection rates for 2010 to 2020 are based on those presented for equipment use and decommissioning in the "Additional Voluntary Action" scenario of the Ecofys study (Ecofys, 2005). These projection rates reflect the increasing implementation of reduction measures both historically (starting in 1995) and in the future. Implementation is assumed to be complete by 2010. The measures include operator training, equipment repair and replacement, improved gas recycling techniques (deep recovery), and a decommissioning infrastructure. As in the U.S., the projections also reflect the increasing leak-tightness of new equipment. Since the Ecofys study did not provide scenarios for beyond 2020, linear regression was used to extrapolate emissions to 2030 (based on 2010 through 2020 emissions).

In July of 2006, the European Parliament and Council enacted a regulation on fluorinated greenhouse gases that required both operator training and "proper" recovery of SF_6 during equipment servicing and decommissioning. It is assumed that these training and recovery measures are reflected in the "Additional Voluntary Action" scenario used from the Ecofys study.

Japan

For Japan, projection rates were obtained from T. Yokota (2006) and reflect the increasing implementation of reduction measures both historically (starting in 1995) and in the future. Emissions were assumed to remain constant at their 2005 level through 2030, based on T. Yokota's

[20] In countries outside of the U.S., EU, and Japan, it is uncommon for electric utilities to purchase SF_6 for filling new equipment (this SF_6 is usually supplied by the equipment manufacturer). Therefore, most SF_6 purchased is used to fill equipment that is leaking and will therefore be a reasonable indicator of SF_6 emissions from electric utilities.

[21] More information on EPA's SF_6 Emission Reduction Partnership for Electric Power Systems is available at: http://www.epa.gov/electricpower-sf6/index.html

projections through 2020 (Yokota et al., 2005). Because the SF_6 bank in Japan is expected to grow substantially in the future, EPA assumed that implementation of reduction measures would increase in order to maintain the 2005 emission level through 2030.

Other Developed Countries

For all developed countries except the U.S., Japan, and the EU, EPA assumed that emissions would remain constant from 2010 levels through 2030. That is, any system growth was expected to be offset by decreases in the equipment's average SF_6 capacity and emission rate as new, small, leak-tight equipment gradually replaced old, large, leaky equipment.

Developing Countries

For developing countries, which began to install SF_6 equipment relatively recently, all current equipment was assumed to be new. Consequently, as infrastructure expanded, emissions from developing countries were estimated to grow at the same rate as country- or region-specific net electricity consumption projections (EIA, 2009).

Uncertainties

In developing emission estimates for this source, EPA used multiple international data sets and IPCC guidance. The robustness of the bottom-up estimates used for the U.S., Japan, and the EU are believed to have improved from EPA (2006) due to the use of UNFCCC reported data in this updated version of the report (UNFCCC, 2012). 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 U.S., Japan, and the EU.

First, the SF_6 producers represented in the RAND survey do not represent 100 percent of global SF_6 production and consumption. EPA accounted for unreported Chinese and Russian SF_6 production, consumption, and emissions by assuming a relationship between net electricity consumption and SF_6 emissions (i.e., SF_6 consumption/net electricity consumption). 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 SF_6 consumption and net electricity consumption in the rest of the world. Net exports from Russia and China would make the "consumption factor" (SF_6 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 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.[22] Another source of uncertainty is that the relationship between SF_6 emissions and net electricity consumption varies from country to country, even when imports and exports are properly accounted for. [23]

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[22] 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.

[23] S. Reiman and M. Vollmer of EMPA have performed a preliminary analysis of this relationship, comparing the SF_6 emission reported through national inventories to the net electricity consumption reported by EIA. They find that the ratios between these two values vary by more than a factor of ten.

Second, the RAND survey's attribution of SF_6 sales to particular end uses is also uncertain, since SF_6 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 SF_6 sales that the survey attributes to utilities could have actually have been 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 uses a lifetime of 40 years (Ecofys, 2005); however, other publications have estimated the lifetime at 30 years (IPCC, 2000). The difference is important because the amount of equipment manufactured 40 years ago is considerably smaller than equipment manufactured 30 years ago. If the average lifetime of equipment were assumed to be less than 40 years, then the estimate of 2003 global emissions would increase.

Fourth, for countries other than the U.S., Japan, EU-25+3, and countries that have reported to the UNFCCC, EPA assumes 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.

Finally, emission projections are based on the assumptions that emissions in developing countries will increase with increasing net electricity consumption. 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 1970's resulting in a reduction in the amount of SF_6 required in switchgear (Ecofys 2010).

Table C-5 presents historical and projected emissions for all countries.

7.2.5 Primary Aluminum Production (PFCs)

EPA used reported emissions from the UNFCCC flexible query system (UNFCCC, 2012) and National Communications reports for all countries where data were available.

For countries for which there was no reported UNFCCC emissions data, EPA calculated country-specific emission estimates from primary aluminum production using historical and forecasted country-specific production data and cell type-specific emission factors. This section first discusses the historical and projected activity data utilized and then discusses the methodology used to develop PFC emission factors for historical and projected emissions.

Historical Activity Data

EPA estimated primary aluminum production for all aluminum-producing countries based on data from USGS Mineral Yearbooks for Aluminum (USGS, 1995 through 2011a). Country-specific aluminum production was disaggregated to cell type using historical global percentages (for 1990–2010) derived from IAI's *Results of the 2010 Anode Effects Survey* report (IAI, 2011).

Projected Activity Data

For 2010, country-specific production estimates were based on estimates from the *USGS 2010 Mineral Yearbook: Aluminum* (USGS, 2011a).

Country-specific production projections from 2015 to 2030 were estimated based on a combination of either applying the global aluminum production compounded annual growth rate of 2.5 percent per year as reported by the IPCC (Martchek, 2006) to the 2010 country-specific production estimate, or for certain countries, specific production projections provided in comments from USGS (USGS, 2011b). For countries with newly developed primary aluminum production (e.g., Qatar and Saudi Arabia) or newly re-commissioned primary production (e.g., Nigeria), the production projections were based on expected production capacity in future years.

Country-specific aluminum production for 2010 was disaggregated to cell type using the historical global percentages derived from IAI (2011) for 2010. Country-specific production projections from 2015 to 2030 were first disaggregated into "existing" or "new-build" production by comparing a country's production projection against that countries total facility nameplate capacity in 2010. Production less than or equal to a country's capacity in 2010 was consider existing production, with production greater than considered new-build production. Existing production was disaggregated to cell type assuming the historical global percentages derived from IAI (2011) for 2010, and new-build production was assigned to the PFPB (i.e., newer) cell type.

Emission Factors and Related Assumptions

EPA estimated PFC emission factors using the Intergovernmental Panel for Climate Change (IPCC) Tier 1 methodology for calculating PFC emissions from primary aluminum production (IPCC, 2006). The technology-based (i.e., cell-type) effective emission factors were derived from smelter operating production and PFC emissions reported in IAI's *Results of the 2010 Anode Effects Survey* report (IAI, 2011).

Historical Emission Factors and Related Assumptions

Cell type-specific (i.e., technology-based) emission factor values were used. Average global cell type-specific emission factors for 1990 through 2010 were derived from smelter operating production and PFC emissions reported in IAI surveys (IAI, 2011). Table 7-9 illustrates these technology-based default emission factors used for 1990 through 2010 emission estimates; specific technology-based default emission factors were also derived for China. The reduction in emission factor values between 1990 and 2010 was the result of several factors, including incremental improvements in smelter technologies and practices, and the construction of state-of-the-art facilities.

Table 7-9: Cell Type-Specific Effective Emission Factors (metric ton CO_2e/metric ton Al)

Cell Type	1990	1995	2000	2005	2010
VSS	4.6	4.1	2.9	2.1	1.0
HSS	2.5	2.4	1.7	1.4	1.3
SWPB	13.8	13.5	12.0	8.1	4.5
CWPB	3.0	2.2	1.3	0.5	0.6
PBPF	2.5	1.0	0.7	0.5	0.3

Source: IAI, 2011

Projected Emission Factors and Related Assumptions

In the analysis, the effective emission factors for each cell technology were assumed to remain constant from 2010 through 2030. The analysis is intended to model the hypothetical scenario in which no further action is taken by the aluminum industry to reduce their emission rates below the 2010 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 CO_2e/metric ton Al) has decreased in recent years (i.e., since 2005). However, IAI member surveys note the significant reductions in AE duration and frequency for all cell-types compared to 1990 through 2009—there has been an 88 percent reduction in anode effect PFC emissions per metric ton since 1990. The IAI had previously established a voluntary goal of reducing global PFC emission intensity by 80 percent by 2010, compared to 1990 levels. Following the achievement of its previous target in 2006, the IAI endorsed a new voluntary target in 2008 of further reducing PFC emissions intensity by at least 50 percent by 2020 as compared to 2006 (equivalent to a reduction of 93 percent compared to 1990). Thus, it is unlikely that actual emissions will be as high as those presented in the analysis. Nevertheless, the analysis does provide an upper-bound estimate of future global emissions.

Uncertainties and Sensitivities

In developing these emission estimates, EPA used multiple international data sets 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.

First, while this study incorporated recent data on total aluminum production by country from USGS Mineral Yearbooks, in order to disaggregate historical aluminum production by cell type EPA used information derived from IAI's *Results of the 2010 Anode Effects Survey* report (IAI, 2011). This information provided the percentage breakout of total global production (which adjusts for non-reporters) by cell type for 1990–2010 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., emission factors) can vary by a factor of five or more across different cell types (IPCC, 2000). In order to disaggregate projected (i.e., post-2010) aluminum production by cell type, EPA first disaggregated into existing or new-build production by comparison with reported nameplate capacity in 2010, then for existing production adopted the percentage breakout of total global production estimated for 2010 for 2015–2030, with new-build production assigned as PFPB. 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 2030.

Second, EPA used a single aluminum production compounded annual growth rate to project country-specific production through 2030 for the majority of countries for which individual projections are not estimated. 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 global rate. This may have a significant impact on emission estimates because production growth may actually be significantly higher than the global rate in countries with major production (e.g., China) or significantly lower in countries traditionally using more emissive cell-technology types (e.g., Russia).

Third, the analysis does not assume that the new IAI goal (i.e., a 93 percent reduction in PFC emission intensity by 2020 from 1990 levels) will be attained (there are no further improvement in PFC intensity levels assumed after 2010). However, it is possible that additional improvement will occur due to changes in the technology mix and continued operational improvements. If this is the case, the analysis may overestimate emissions.

Fourth, EPA used information from IAI (2011) to derive technology-based effective emission factors (metric ton CO_2e/metric ton Al) for 1990–2010. The IAI surveys while representative do not

cover the entire global primary aluminum production sector.[24] Therefore, while the IAI adjusts for non-reports, these data may under- or overestimate the true global emission factors (and hence the emissions) for the analysis. In addition, as previous discussed, EPA assumed the emission factors estimated for 2010 when estimating emissions for 2015–2030. Therefore, while these emission factors derived from the 2010 *Anode Effect Survey* are representative of the technology in place through 2010, these emission factors may not truly represent values that would be derived from reported data for the technology in place through 2030.

Table C-6 presents historical and projected emissions for all countries for this source for the analysis.

7.2.6 Magnesium Manufacturing (SF_6)

EPA developed SF_6 baseline emissions for three magnesium metal processes: primary production, die-casting, and recycling-based or secondary production. Country-specific emission estimates are expressed as projections based on reported UNFCCC data or as the product of process-specific emission factors and historical and forecasted production. This section first discusses the historical and projected activity data utilized, specifically country-specific production and anticipated market trends (projections), such as future plans to expand, shift, or curtail production. Next, it discusses the process-specific emission factors used to estimate historical and projected emissions.

In the absence of emission control measures, the rapid growth of the magnesium manufacturing industry would be expected to result in significantly increased future SF_6 emissions from magnesium production and processing. However, efforts in recent years to eliminate the use of SF_6 in this application around the world have reduced this potential growth in emissions. In 2003, the U.S. partnership catalyzed a global industry commitment through the International Magnesium Association (IMA), which represents approximately 80 percent of magnesium production and processing outside of China, to eliminate SF_6 emissions from magnesium operations by the end of 2010 (EPA, 2010). Regulatory efforts in Europe and Japan, and clean development mechanism (CDM) projects in Brazil and Israel have resulted in significantly reduced emissions.

Historical Emissions

Activity Data

Historical estimates were based on emissions data obtained from the UNFCCC flexible query system where data were available from 1990 through 2009 (UNFCCC, 2012). The time series was available for most A1 countries, however gaps existed in the time series for the majority of the NA1 countries. For the remainder of the historical time series, EPA utilized the follows projection methodology:

- When data for an incremental reporting year was not available, the next adjacent reporting year value was utilized as a proxy (e.g., data reported for 1996 was utilized for 1995).

[24] Coverage of the annual survey of PFC emissions from IAI member and non-member aluminum producers has almost doubled from a global aluminum production of 12 Mt in 1990 to 22 Mt (53 percent of the industry's production) in 2010. The IAI is striving to increase the global aluminum production coverage of its annual Surveys to over 80 percent. (IAI, 2011).

- When data for an incremental reporting year was not available, the value from the next available reporting year was utilized (e.g., data reported for 1995 was held constant for the 1990 value).

This section summarizes process-specific production data used to estimate historical emissions.

Primary Production

Countries for which EPA estimated emissions from primary magnesium production include: Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, the Russian Federation, Spain, Ukraine, and the United Kingdom. Data for primary magnesium production for all countries for 1990 to 2008 were obtained from the U.S. Geological Survey (USGS, 2007 and 2009).

Die-Casting Production

- *European Union (EU).* For Portugal, Spain, and the United Kingdom, EPA estimated historical SF_6 emissions using information derived from Harnisch and Schwarz (2003). 2001 emissions were estimated as the product of a region-specific emission factor and country-specific data on SF_6-based magnesium casting 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) the quantity of magnesium used per car in the U.S. Between 1990 and 1995, the quantity of magnesium used per car in the EU were estimated to have increased by 30 percent. Thus, casting SF_6 emissions in the EU based on car production were assumed to have increased by 30 percent between 1990 and 1995, since emission factors were believed to have remained constant over the same period. 1995 emission estimates were derived from the 1995 emissions presented by Harnisch and Schwarz for the EU as a whole; country-specific emissions were calculated by multiplying the aggregate EU emission estimate (20 metric tons SF_6) by each country's share of total SF_6-based EU die-casting production in 2001. 2000 emissions were estimated by linearly interpolating between the 1995 and 2001 data. For years 2000 through 2035, emission estimates were simply calculated as a product of emission factor and die-casting. For 1996 to 2000, estimates were based on linear interpolation.

- *China (2000, 2005 and 2010 only).* EPA utilized Chinese casting volume for the years 2000, 2005 and 2010 from Edgar (2004).

- *Other Countries.* Casting estimates for other countries and other historical years were not readily available. Consequently, die-casting for the years 1990 to 2008 was estimated as a function of automobile production. For example, for Brazil, China (except 2000, 2005 and 2010), Russia, and Ukraine, casting 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 to 2008 production data was obtained from (OICA, 2010). For countries that do not produce automobiles but have growing casting industries such as Kazakhstan and Israel (IMA, 2002), production was estimated from the ratio of primary production to casting production for a similar country. Russia was used as a proxy for estimating production in Kazakhstan, while the U.S. was used as a proxy for Israel. Taiwan is estimated to acquire 50 percent of Japan's die casting activity starting in 2005.

Recycling-based Production

Recycling-based production, or secondary production, for Brazil, China, Russia, and the UK was estimated using die casting activity and a "remelt factor" of 30 percent. The secondary production to die casting ratio can range from 30 to 55 percent across countries that actively recycle scrap magnesium (Edgar, 2006) and 30 percent was chosen as a conservative default for those countries where emissions are calculated for this source. The Czech Republic was reported to have a new recycling plant come online in 2002 and is expected to have an annual growth rate of 3.4 percent through 2010 and then 1.7 percent from 2011 to 2035 (Webb, 2005). Table 7-10 presents the growth rates used in this analysis.

Table 7-10: Annual Growth Rates for Primary, Casting and Recycling Production (Annual Percent Increase)

Year	Casting Annual Growth Rates (percent)		Recycling Annual Growth Rates (percent)
	Asia	Europe[a]	World
2000-2005	9.6	3.4	Same as Casting
2005-2010	9.6	3.4	Same as Casting

[a] Limited projection efforts conducted to fill historical projection gaps in the automobile production benchmarking approach described above.

Historical Emission Factors and Related Assumptions

In this analysis, SF_6 emissions are conservatively assumed to be equivalent to SF_6 consumption (i.e., it is assumed that no SF_6 is destroyed during the metal processes). This may overstate emissions, as recent EPA studies have shown that 5 to 20 percent of the SF_6 is degraded during its use as a cover gas during at least one type of casting process (Bartos et al., 2003). For all countries that EPA estimated emissions for, Table 7-11 and Table 7-12 summarize the emission factors utilized to estimate historical emissions for each of the production processes. The emission factor for primary production was based on measurements made in 1994 and 1995 by U.S. producers. Due to the similarity between the primary and recycling production processes, the emission factor for recycling production was assumed to be the same as that for primary production. The emission factor for die-casting was drawn from a 1996 international survey of die-casters performed by Gjestland and Magers (1996).

Table 7-11: Emission Factors for Primary Casting and Recycling Production (1990 – 1995)

Process	Emission Factor (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

[a]Emission factors utilized to estimate emissions from Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and United Kingdom as appropriate.

Table 7-12: Emission Factors for Primary Casting and Recycling Production (2000 – 2005)

Process	Emission Factor (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

[a]Emission factors utilized to estimate emissions from Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and United Kingdom as appropriate.

In China, in 1990 and 1995 the main cover gas mechanism for primary production was sulfur dioxide (SO_2) generated from the application of solid sulfur powder. Therefore, China's SF_6 emissions from magnesium primary production in 1990 and 1995 are assumed to be zero. In 2000, SF_6 usage is estimated to account for 10 percent of primary production and the remaining was SO_2. For 1990 to 2000 SF_6 is estimated to account for 50 percent of recycling production in China; the share of SF_6 for recycling drops to 10 percent in 2005 and zero in 2010. For 2000 and 2005 SF_6 is estimated to account for 50 percent of die casting production, dropping to 10 percent in 2010.

Die casting activity using SF_6 in Portugal and Spain is estimated to account for 60 percent and 10 percent of die casting production in 2005 and 2010, respectively, under the EU phase-out. Similarly, magnesium recyclers in the U.K. have switched to SO_2 since 2000, and U.K.'s SF_6 emissions from magnesium recycling from 2000 to 2035 are therefore assumed to be zero. Kazakhstan, Portugal, Spain, and Ukraine do not recycle magnesium in significant quantities.

Projected Emissions

Activity Data

Projected emission estimates were based on emissions data obtained from National Communications (NC), where available. Estimates for some years were available for four countries (Argentina, Australia, Macedonia, and New Zealand). Voluntary SF_6 cover gas use phase-out is assumed by 2010 for Austria, Denmark, France, Germany, Italy, Norway, Poland, Sweden, and Switzerland in compliance with the EU phase-out schedule. U.S. phase-out is assumed to be implemented by a majority of companies in 2010 under the U.S. Magnesium Industry Partnership goal (EPA, 2010). Canada and Japan are assumed to phase-out SF_6 usage from 2010 through 2020. These estimates were incorporated into the time-series as follows:

- When data for projected years was not available for countries with small emissions, emissions were held constant from the most recent year reported (e.g., 2005);
- European Union countries were projected to have emissions in 2010 that were 10 percent of estimated emissions in 2005; emissions from 2015 to 2030 were assumed to be zero;
- Canada was projected to have emissions in 2010 through 2020 that were 50 percent of estimated emissions in 2005; emissions from 2025 to 2030 were assumed to be zero;
- Japan was projected to have emissions in 2010 through 2020 that were 50 percent of estimated emissions in 2005; emissions from 2025 to 2030 were assumed to be zero; and

- The United States was projected to have emissions reductions in 2010 by 40 percent relative to the reported 2005 emissions; emissions were projected to be reduced by 25 percent in 2015 and 2020, then hold constant at the 2020 level to 2030.

This section summarizes the process-specific activity data and emission factors used to estimate projected emissions in the absence of NC data. Projected emissions were calculated by EPA for Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and the United Kingdom.

This section discusses the regional growth rates and country-specific assumptions used to forecast magnesium primary production, casting, and recycling-based production from 2010 through 2035. Growth rates are summarized in Table 7-13. In general, annual growth rates used in this analysis were assumed to account for new facility construction as well as 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 growth rates were based on information supplied by Webb (2005) for the rest of the countries' estimates. Recycling is linked to die casting and the associated growth rates for that production process.

Primary Production

- *Growth Rates.* In all countries where EPA projected emissions (i.e., Brazil, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine and the U.K.) except China, EPA assumed primary production will grow 3.4 percent per year between 2001 and 2010. Between 2011 and 2020, growth was assumed to decrease to an annual rate of 1.7 percent. From 2000 to 2005, Chinese primary production more than doubled, however, based on data reported in USGS (2009) production contracted due to the global economic downturn. Primary production in China was projected to grow at 5 percent from 2010 through 2020 and then hold steady at 2020 levels to 2030.

Die-Casting

- *Growth Rates.* In Asia (except China) and Russia, die casting is expected to grow at 9.6 percent from 2006 to 2010, and 4.8 percent from 2011 to 2035 (Webb, 2005). For Europe and other countries such as Brazil, Israel, Kazakhstan and Ukraine, die casting is estimated to grow at 3.4 percent from 2006 to 2010, and 1.7 percent from 2011 to 2035. The decrease after 2010 reflects the likelihood that the recent period of growth will not continue indefinitely. For China, casting is assumed to grow annually at approximately 10 percent from 2005 to 2010 (Edgar, 2004). From 2010 to 2035, casting in China is estimated to grow at 5 percent, or half of the 2005 to 2010 rate. 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.

Recycling-based Production

- *Growth Rates.* For all countries where EPA estimated emission projections, recycling growth rates were set equal to casting growth rates.

Global Activity Growth Rates

Table 7-13 presents the growth rates used in this analysis.

Table 7-13: Annual Growth Rates for Primary Casting and Recycling Production (Annual Percent Increase)[a]

Year	Primary Production Annual Growth Rate[b] (percent)		Casting Annual Growth Rate (percent)					Recycling Annual Growth Rate[b] (percent)
	China	ROW	ROW	Asia	China	Europe	Russia	World
2006-2010	3.5	3.4	3.4	9.6	10.0	3.4	9.6	Same as Casting
2011-2035	5.5[c]	1.7	1.7	4.8	5.0	1.7	4.8	Same as Casting

[a] See text above.
[b] Source: Primary and casting growth rates are based on Webb (2005). For recycling, it is assumed that growth rates will be driven by increased use in automotive applications; consequently, growth rates will be the same as casting estimates.
[c] Annual growth for China estimated to be 5.5 percent through 2020 and then held at zero for 2020 through 2035.

Projected Emission Factors

EPA assumed the projected emission factors remain constant from 2010 to 2035. EPA's emission projections are intended to model the hypothetical scenario in which no additional action is taken by magnesium producers or processors to reduce their SF_6 emission rates below the levels observed during the late 1990s. In fact, many producers and processors have already taken significant steps to reduce their emission rates and to achieve the IMA goal of eliminating SF_6 emissions from magnesium operations by the end of 2010. These include research programs in several countries and, in some cases, the adoption of alternative cover gases such as HFC-134a and SO_2.

Table 7-14 summarizes the emission factors EPA used to estimate emissions for this scenario from 2010 to 2035 where data was obtained from the EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. The 2000 emission factor for primary production, which is held constant from 2010 to 2035, was based on measurements made by four producers (i.e., producers with domestic U.S. and international operations) (EPA, 2010).

In China, it is assumed that some Chinese magnesium producers have begun to utilize SF_6 in an effort to produce better quality magnesium for the world market. Between 2000 and 2005, the fraction of Chinese magnesium producers using SF_6 is assumed to have grown from zero to 10 percent. From 2005 through 2035, SF_6 cover use is assumed to remain at 10 percent of total market cover gas usage, with the remaining Chinese primary producers still using SO_2 (Edgar, 2006). Those Chinese producers using SF_6 are assumed to emit at the rate shown in Table 7-14.

For all countries except the U.K., the emission factor for recycling was conservatively assumed to be the same as primary production. For the U.K., SO_2 will continue to be the primary cover gas system, so emissions from these sources will be zero. 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).

In Brazil and Israel, CDM projects are projected to significantly reduce emissions starting in 2010. RIMA, a large scale magnesium production and processing facility in Brazil implemented a full conversion so SO_2 for its primary, die casting, and recycling activities (UNFCCC, 2010a). Dead Sea Magnesium, in Israel, implemented a conversion of its primary production to HFC-134a (UNFCCC, 2010b); because HFC-134a has a GWP of 1,300, these emissions were included with an estimated mass usage ratio of 50 percent that of SF_6.

Table 7-14: Emission Factors for Primary Casting and Recycling Production (2010 – 2035)

Process	Emission Factor (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

[a] Emission factors utilized to estimate emissions from Brazil, China, the Czech Republic, Israel, Kazakhstan, Portugal, Russia, Spain, Ukraine, and United Kingdom as appropriate.

Uncertainties and Sensitivities

In developing these emission estimates, EPA used multiple international data sets and the most recent IPCC guidance on estimating emissions from this source (IPCC, 2006). Nevertheless, the resulting emission estimates are subject to considerable uncertainty.

Historical and current 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 for casting. In addition, emission rates vary widely across different processes and over time. 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).

Projected emissions from magnesium production and processing are sensitive to (1) estimated activity growth rates, and (2) assumptions regarding the adoption and/or retention of alternate melt protection technologies. EPA has used relatively high activity growth rates to project emissions; therefore, slight changes in these rates could lead to large changes in projected emissions. Second, this analysis assumes that some but not all Chinese magnesium producers have adopted SF_6 in place of solid sulfur as they seek to increase the quality of their metal. Because China is currently the world's largest producer of magnesium, greater penetration of the Chinese market by SF_6 could significantly increase both Chinese and global emissions. On the other hand, penetration of the Chinese casting market by alternate cover gases would lower Chinese emissions below those projected in this analysis.

Finally, this analysis does not account for the potentially significant impact of unannounced mitigation projects funded by developed countries under the Clean Development Mechanism (CDM) of the Kyoto Protocol. While projects in Brazil and Israel have been accounted for, additional CDM projects could decrease SF_6 emissions from magnesium production and processing in China and other developing countries.

Table C-8 presents historical and projected emissions for all countries for this source for the analysis.

7.2.7 Semiconductor Manufacturing (HFCs, PFCs, NF_3, and SF_6)

PFC, HFC, NF_3, and SF_6 emissions are from two repeated activities in semiconductor manufacturing: (1) cleaning of chambers used to deposit thin layers of insulating materials, a process referred to as chemical vapor deposition (CVD) chamber cleaning, and (2) etching intricate patterns into successive layers of insulating films and metals, a process referred to as plasma etching. Film deposition and etching processes begin with the semi-conductive crystalline silicon (Si) wafer and continues as successive films (layers) are deposited and etched to form and complete a device (i.e.,

the connection of all the elements of the device). Industry reports indicate that approximately 70 to 80 percent of emissions result from chamber cleaning processes and 20 to 30 percent from etching processes (IPCC, 2002; Beu and Brown, 1998).

The absence of emission control measures, the rapid growth of the semiconductor industry (11 to 12 percent per year through the late 1990s) and the increasing complexity of microchips could potentially result in significantly increased projected emissions from semiconductor manufacturing. Due to this possibility, the U.S. EPA and the U.S. semiconductor industry launched a voluntary partnership to reduce PFC 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 U.S., EU, Japan, South Korea, and Taiwan[25] - have voluntarily committed to reduce HFC, PFC, NF_3, and SF_6 emissions to 90 percent of 1995 levels by 2010.[26] For this analysis it was assumed that all of these WSC countries met and maintained the WSC goal[27] (ITRS, 2009 and WSC, 2010). While China joined the WSC in June 2006, it has not yet committed to a reduction goal. EPA assumed though in this analysis that China will set and achieve a reduction target. EPA based this assumption by analyzing multiple alternative emissions reduction scenarios/growth scenarios of total manufacture layer area (TMLA) for semiconductor devices for China presented in the article *Modeling China's semiconductor industry fluorinated compound emissions and drafting a roadmap for climate protection* (Bartos et al, 2008). Based on EPA's analysis of how the various scenarios align with China's historical emissions and other world historical emissions and projections, 2012 was selected as the reduction baseline year for China with a 10 percent reduction goal by 2010.[28]

Historical HFC, PFC, and SF_6 Emissions (1990 through 2005)

Historical country-reported emissions (1990 through 2005) from the manufacture of semiconductors were available through the UNFCCC for most Annex I countries. EPA, where possible, elected to use the Annex I reported emissions data for this analysis. However, a large share of world semiconductor manufacturing capacity is represented in many non-Annex I countries, such as China, Taiwan, and Singapore. To achieve as much consistency as possible while using the UNFCCC emissions data, EPA summed the total amount of reported emissions from Annex I countries for PFCs, HFC, and SF_6 separately. These three totals, one for PFC, one for HFC, and one for SF_6, were then each scaled up using country-specific capacity shares to determine total emissions for the world. This method is demonstrated in the following equation:

[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 as they are treated separately under the WSC and have different industry associations.

[26] 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.

[27] These assumptions are based on the WSC Joint Statement (May 2010) which indicated that the WSC is on track to meet their reduction goals, and information from the ITRS 2009 (Table ESH3a or b) which indicates that the WSC goal will be maintained through 2024.

[28] This assumes that China's TMLA grows at an intermediate rate (13.5 percent per year) in future years.

Where:

Total World Emissions$_{i,y}$	= estimated total world emissions of gas type *i* in year *y*
Total Reported Annex I Emissions$_{i,y}$	= total reported emissions for Annex I countries of gas type *i* in year *y*
Total Capacity Share Reporting Annex I countries$_{i,y}$	= total capacity share of the world for reporting Annex I countries for gas type *i* in year *y*
i	= gas type (PFC, HFC, or SF_6)
y	= year

Total world emissions for 1990, 1995, 2000, and 2005, along with estimated country-specific capacity shares were used to determine country-specific historical emissions for all non-Annex I countries and Annex I countries without reported historical emissions using the following equation:

$$\textit{Country-Specific Historical Emissions}_{i,y} = \textit{Total World Emissions}_{i,y} * \textit{Country-Specific Capacity Share}_{i,y}$$

Historical Country-Capacity Shares

Global activity data comprise historical and projected global Si consumption by linewidth and device type (i.e., memory vs. logic) provided by VLSI Research, Inc. (VLSI, 2003). For 1990 through 2005, this activity was apportioned to individual countries and regions using information from the World Fab Watch (WFW) databases on manufacturing capacity by linewidth and country (WFW, July 1996, 2001, 2002 and April 2003 Editions) to determine country-specific capacity shares for 1995, 2000, and 2005.[29] In using capacity shares to apportion emissions EPA made the assumption that TMLA is the basic unit of activity and that the distribution of F-GHG reduction technologies during this period does not vary appreciably across countries.

NF_3 Emissions

NF_3 is not a GHG that is included in National Inventories per the UNFCCC. Therefore to estimate NF_3 emissions EPA could not rely on UNFCCC emissions data and country capacity shares as was done for HFCs, PFCs, and SF_6. Instead, to estimate NF_3 emissions EPA used a method which took into account the estimated share of NF_3 emissions of total high global warming potential emissions in each five year increment. Using emissions data reported through the EPA/Semiconductor Voluntary Partnership EPA estimated percentages of emissions by gas (PFC, HFC, SF_6, and NF_3). Partnership emissions data was available for the time series 1995-2010; five years of shares data were simply averaged to determine the share of emissions by gas in a certain year (e.g., 2001-2005 data were used to develop average shares for 2005). Emissions shares by gas in historical years were assumed to be equal to 1995 shares. Using these developed shares and already reported and estimated PFC, HFC, and SF_6 emissions EPA estimated historical NF_3 emissions for 1990-2005 using the following formula:

*[Sum (PFC, HFC, SF_6 emissions in year X) / Sum (Percentage of PFC, HFC, SF_6 emissions of total emissions, including NF_3, in year X)] * Percentage of NF_3 emissions of total emissions in year X = NF_3 emissions in year X*

[29] Country-specific capacity shares in 1990 were assumed to be equivalent to those in 1995.

Projected Emissions (2010 through 2030)

For countries that are not members of the WSC, emissions from 2010 to 2030 were estimated by growing each PFC, HFC, and SF_6 emissions at a rate equivalent to the 5 year compound annual growth rate of each country's gross domestic product (GDP). GDP growth rates were determined using raw GDP data from the US Department of Agriculture (USDA, 2009). For non-WSC member countries EPA used the same method as described in the historical emissions section to estimate NF_3 emissions. EPA assumed a constant share of NF_3 emissions for 2010-2030.

For all WSC member countries, as discussed above, EPA assumed that they each individually achieved the voluntary emissions reduction goal of 10 percent below the voluntarily agreed-upon baseline year by the year 2010, for each PFC, HFC, NF_3 and SF_6 emissions (WSC, 2010). EPA assumed that the WSC countries consistently met this goal in all subsequent years (2015-2030)[30] (ITRS, 2009). EPA allocated WSC goal-level emissions by gas type using the same shares of emissions by gas as were used for non-WSC countries.

For years prior to 2020, China's PFC, HFC, NF_3, and SF_6 emissions were estimated to grow at a rate equivalent to the 5 year compound annual growth rate of their GDP. As discussed above, EPA assumed that China will commit to a 2012 reduction baseline year and achieve a 10 percent reduction goal by 2020. EPA assumed this under the condition that China's future TMLA will growth at a rate of 13.5 percent annually (Bartos et al, 2008). Due to limited information, it was assumed that in 2025 and 2030 China will maintain emissions at their assumed reduction goal level.

Uncertainties and Sensitivities

EPA based projected sector emission growth rates on a one-to-one scale with county GDP growth rates. However, it may be appropriate to scale the country GDP growth rates by some factor before applying them to determine future emissions for the semiconductor manufacturing sector. EPA may consider these potential scaling factors in future analyses.

This analysis also projects emissions assuming that the current semiconductor manufacturing process continues and that currently available abatement technologies are used to reduce the resulting fluorinated greenhouse gas emissions. It does not model a possible future in which fluorinated greenhouse gases are no longer used in semiconductor manufacturing at all. Thus, this analysis may overestimate emissions. Alternatively, there is a possibility that the analysis underestimates emissions by assuming that China sets and achieves a voluntary reduction goal with the WSC. If this does not materialize, China's emissions, and hence total world emissions, may be substantially higher than projections calculated in this analysis.

Lastly, this analysis assumed that the shares of emissions by gas will be constant from 2010-2030. This assumption was made because it cannot be known at this time what new process and technologies will be used in semiconductor manufacturing, which is a high-tech and rapidly evolving industry. However, if new technologies come online in future years the shares of emissions may likely change.

Table C-7 presents historical and projected emissions for all countries for this source for the analysis.

[30] The ITRS 2009 indicates that the 10 percent absolute reduction from a baseline year will be maintained through 2024. EPA assumes this goal is also met in 2030.

7.2.8 Flat Panel Display Manufacturing (SF_6, PFCs, and NF_3)

The flat panel display (FPD) sector is a new source category in this report. Country-reported emission estimates were not available for this sector and, as a result, EPA used the IPCC Tier 1 methodology for estimating emissions from the manufacture of FPDs (IPCC, 2006). The basic Tier 1 equation for estimating emissions is as follows:

$$FC_i = EF_i \times CU \times CD$$

Where:

FC_i	=	Emissions of gas *i* (mass)
EF_i	=	Emission factor for gas *i* (mass/m^2)
CU	=	Fraction of annual plant production capacity utilization (%)[31]
CD	=	Annual maximum design capacity of substrate processed (m^2)

The main source of data for this source category is the *DisplaySearch Q4'09 Quarterly FPD Capacity Database & Trends* Report ("DisplaySearch database") (DisplaySearch, 2009). This database supplies historical and projected annual data through 2012 about all FPD facilities in the world, including location (country), maximum design capacity for substrate processing of a facility (in 1,000 m^2), and in some cases the utilized capacity of a facility (percent).

As discussed in Section 4.8 of this report, SF_6, PFCs (CF_4), and NF_3, are used for chemical vapor deposition cleaning processes during the manufacture of FPDs and then in plasma dry etching during manufacture of arrays of thin-film transistors on glass substrates, which switch pixels of liquid crystal displays and organic light emitting diode displays.

Historical and Projected Activity Data

The activity data for emission estimates from FPD manufacturing is utilized capacity (m^2) of FPD area produced. This is derived from maximum design capacity expressed in area (1,000 m^2) for each country and the world. This maximum design capacity is converted to utilized capacity (m^2) by applying a utilized capacity factor (%). For simplicity, a single, global average utilized capacity factor of 88 percent 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 capacity factors (%) for all years provided in the DisplaySearch FPD database (DisplaySearch, 2009).[32]

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

[31] CU is assumed to be equivalent to 88 percent. See footnote 32.

[32] In the DisplaySearch FPD database capacity utilizations (%) were only available for the years 2005-2010. 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 percent). While the DisplaySearch databases provided some country-specific capacity utilizations for specific fabs in a country, there were many gaps in this data. Therefore using the database may have lead to an underestimation of actual emissions.

- **2000, 2005, and 2010:** EPA extracted total maximum design capacities by country and for the world in 2000, 2005, and 2010 directly from the DisplaySearch Q4 2009 PV database (DisplaySearch, 2009).
- **1990, 1995, 2015, 2020, 2025, and 2030:** EPA determined total world maximum design capacities in each of these years by applying 5 year, global compound annual growth rates (CAGRs) for each period. These 5-year world CAGRs were assumed based on expert judgment about past demand in the FPD market.

  Using the world maximum design capacity estimate for each year as well as country-specific shares of world capacity (or "capacity shares"), country-specific CAGRs for each five year interval are determined using the following equation:

Where:

Yf	=	future year
Yo	=	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, which were determined using country and world capacity data extracted from the DisplaySearch Q4 2009 FPD database (DisplaySearch, 2009). Country-specific capacity shares for 2015 through 2030 were assumed based on expert judgment of how the market may look through 2030.[33]

Maximum design capacity for each country was then forecasted or backcasted by applying a country-specific 5 year CAGR to maximum design capacity in the appropriate adjacent time period.

As noted above, once total maximum design capacities were determined for each country and the world for the 1990-2030 time series, these values are converted to utilized capacity (m^2) using a world average utilized capacity factor.

Emission Factors and Related Assumptions

To determine emissions for each country, the total utilized capacity (m^2) is converted to PFC, NF_3, and SF_6 emissions ($MtCO_2e$) using IPCC Tier 1 emission factors for PFCs, NF_3, and SF_6 ($MTCO_2e/m^2$) (IPCC, 2006).

Use of Abatement Strategies

Without incentives and or emissions targets, it is assumed that the FPD sector does not employ abatement technologies. The World LCD Industry Cooperation Committee (WLICC) goal, which is

[33] It was assumed that the competition between Taiwan and South Korea leads to the equal country shares in 2030. China's share is expected to increase to meet rising domestic (internal) demand for FPDs.

voluntarily established, creates reason for Japan, South Korea, and Taiwan to employ abatement technologies at facilities in their countries in 2010 and beyond. The WLICC goal, formed in 2003, established a fluorinated- GHG (F-GHG emission) target of 0.82 $MtCO_2e$, equivalent to 10 percent of the projected business-as-usual 2010 emissions (Bartos, 2010).[34]

Therefore, as part of the emissions projections in this report, it was assumed that abatement strategies were used to achieve the WLICC goal in Japan, South Korea and Taiwan.[35] The goal of was assumed to be split equally between the three countries involved. To determine emissions with the use of abatement to meet the WLICC goal in any given year, EPA used the following equation:

Where:

$a_{g,i}$	=	fraction of gas g emissions abated in country *i*
$d_{g,i}$	=	abatement efficiency for gas g in country *i*
g	=	gas index (PFC or SF_6)
i	=	country index

Due to limited availability about abatement practices in WLICC countries, as a starting point, EPA assumed 90 percent abatement efficiency for PFCs for each country, for each year. This abatement efficiency is the default abatement efficiency value published in the 2006 IPCC Guidelines (IPCC, 2006). The abatement efficiency used as starting point for SF_6 for each country for each year is assumed to be an achievable 100 percent because SF_6 is straightforward, that is, SF_6 has the highest GWP and it is equally cost effective to abate compared to NF_3 and PFCs.

Next, EPA determined the fraction of emissions abated and the abatement efficiency that WLICC countries must achieve to meet the goal in 2010-2030. EPA used the following algorithm:

1. An emissions goal was set at for each country for 2010-2030 at one third of the total WLICC goal; this equated to approximately 1.00 $MtCO_2e$ per member-country.

[34] The WLICCC is a group of the three participating countries' LCD trade organizations whose main purpose is to ensure the future of the LCD industry through collaboration on environmental issues such as emissions and waste. This goal was set in response to the increasing growth in the F-GHG emissions due to the 96 percent share of the global FPD manufacturing market that these three countries hold.

[35] The WLICC goal takes into account NF_3 emissions. Therefore for this analysis the "NF_3 portion" of the WLICC target was removed. The portion was estimated based on historical F-GHG emission estimates available to EPA through working with the WLICC to assess and analyze the data reported by the three country industry associations. The portion of NF_3 emissions in the WLICC goal was assumed to be 78 percent.

2. The fraction of SF_6 emission abated was assumed to be 100 percent at an abatement efficiency of 100 percent, equating to zero SF_6 emissions.[36] This results in all of the WLICC countries' goal emissions to be allocated to NF_3 and PFC emissions.

3. The remaining WLICC goal emissions were allocated to NF_3 and PFC using an 80 percent and 20 percent split, respectively.[37]

Through using this method EPA ensured that the WLICC goal could be realistically met based on the estimated emissions without the use of abatement.

Uncertainties and Sensitivities

These global emissions projections are highly sensitive to the assumption that China's domestic demand for FPDs will substantially increase in the future (DisplaySearch, 2010); 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.

Table C-9 presents historical and projected emissions for all countries for this source for the analysis.

7.2.9 Photovoltaic Manufacturing (PFCs and NF_3)

The photovoltaic manufacturing (PV) sector is a new source category in this report, and country-reported emission estimates are not available for this sector. Due to the lack of country-reported data, EPA used the IPCC Tier 1 methodology for estimating emissions from etching and cleaning processes used at PV manufacturing facilities (IPCC, 2006). The basic Tier 1 equation for estimating emissions is as follows:

Where:

FC_i	=	Emissions of gas *i* (mass)
EF_i	=	Emission factor for gas *i* (mass/m^2)
CU	=	Fraction of annual plant production capacity utilization (%)[38]
CD	=	Annual maximum design capacity of substrate processed (m^2)

The main source of data for this source category is the *DisplaySearch Q4'09 Quarterly PV Cell Capacity Database & Trends Report* ("DisplaySearch database") (DisplaySearch, 2009). This database supplies historical and projected annual data through 2013 about all PV facilities in the world, including location (country), type of technology manufactured at a facility (crystalline silicon, amorphous

[36] This assumption was made, again, because SF_6 is because of its higher GWP and as cost effective to abate as NF_3 and PFCs.

[37] This estimate was based on expert knowledge on the relative use and emissions of these gases.

[38] Cu is assumed to be equivalent to 100 percent; that is the maximum design capacity is assumed to be utilized.

silicon, 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.

As discussed in section 4.10, and shown in the DisplaySearch database, there are a variety of substrates used in the production of PV cells, including crystalline silicon, amorphous silicon, and other thin-films. Manufacturing processes of PV cells with other thin film technologies do not utilize F-GHGs, whereas manufacturing processes of PV cells with crystalline silicon (c-Si) PV cells and amorphous silicon (a-Si) and tandem a-Si/nanocrystaline (nc) silicon PV cells do use F-GHGs. Therefore for this analysis the PV market considered was limited to c-Si and a-Si PV cells.

Historical Activity Data

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

Historical maximum design capacities[39], in units of MW, are determined by the following various methods:

- **1990 and 1995:** Maximum design capacities in these years are assumed to be 0 MW because the sector was so small in this time period that any associated manufacturing emissions would be negligible.
- **2000, 2005, and 2010:** Maximum design capacities by country and for the world in 2000, 2005, and 2010 are extracted directly from the DisplaySearch database (DisplaySearch, 2009).

Maximum design capacity is converted to area of produced PV panels (m^2), the activity data, using technology-specific and time-varying market shares and average electrical conversions 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:

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

Technology market shares[40] and average conversion efficiencies[41] are determined using data from the DisplaySearch database (DisplaySearch, 2009). In instances where data was not available to calculate these values (i.e. DisplaySearch information was incomplete or for future years) technology conversion efficiencies and market shares are assumed based on historical data and expert judgment.

[39] Includes maximum design capacity for crystalline and amorphous silicon, the two technologies that use PFCs in their manufacturing processes.

[40] For this report technology market shares are calculated based on a PV market that is assumed to only include c-Si and a-Si technologies.

[41] Technology conversion efficiencies are supplied for some years for both c-Si and a-Si technologies in the DisplaySearch database. For each year this information is supplied a simple average of the available conversion efficiencies is taken for each technology.

Projected Activity Data

Projected maximum design capacities[42], in units of MW, are determined by the following various methods:

- **2015***:* World maximum design capacity in 2015 is extrapolated using the average annual absolute growth in capacity for the world from 2010 through 2013. World maximum design capacities for 2010 and 2013 are extracted directly from the DisplaySearch database (DisplaySearch, 2009).

Using the world maximum design capacity estimate for 2015 as well as country-specific shares of world maximum design capacity (or "capacity shares"), country-specific compound annual growth rates (CAGRs) for 2010 through 2015 are estimated using the following equation:

Country-specific capacity shares for 2010 are determined using the 2010 country and world maximum design capacity data extracted from the DisplaySearch database (DisplaySearch, 2009). Country-specific capacity shares for 2015 were assumed to be equivalent to the shares for 2013, which are also determined using data extracted from the DisplaySearch database (DisplaySearch, 2009).

Maximum design capacity for each country in 2015 is calculated by applying country-specific 5 year compound annual growth rates (CAGRs) for 2010-2015 to maximum design capacity for each country in 2010.

- **2020, 2025, and 2030***:* World maximum design capacities in 2020, 2025, and 2030 are determined by applying 5 year CAGRs for each period. These 5 year CAGRs were assumed to be equivalent to the 2010 through 2015 CAGR.

The methodology that is used to estimate maximum design capacity for each country in 2015 is also used to estimate maximum design capacity for each country in 2020 through 2030. Country-specific capacity shares are held constant through 2030 at 2015 (2013) levels.

Maximum design capacity is converted to area of produced PV panels (m^2), using the conversion equation as described in the previous section.

Emission Factors and Related Assumptions

Area of PV panels (m^2) for each country and the world are converted to emissions ($MtCO_2e$) using the emission factors ($MtCO_2e/m^2$) for c-Si and a-Si, and the respective market shares of each technology in a given year. CF_4 and C_2F_6 are used during manufacture of c-Si PV cells. Tier 1 emission factors both of these PFCs for PV manufacturing are published in the 2006 IPCC Guidelines (IPCC, 2006).

[42] Includes capacity for crystalline and amorphous silicon, the two technologies that use PFCs in their manufacturing processes.

NF_3 is also used during manufacture of a-Si PV cells; however there is no published emission factor for NF_3 used during PV manufacturing. However NF_3 is used routinely for cleaning during the manufacture of a-Si PV cells, and the emissions are not negligible, depending on emissions abatement practices. Therefore EPA developed an emission factor for NF_3 using recently measured, unpublished NF_3-usage and NF_3-emissions data for currently operating a-Si PV manufacturing facilities.

Uncertainties and Sensitivities

Projections

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 fast-growing renewable energy sector, which, in turn is embedded in the relatively slow-growing energy sector. An effort was made to take into account, 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 need for more energy as countries like China and India industrialize, and a growing understanding of the environmental effects of traditional sources of energy.

While this perspective was useful in framing these projections, there are many uncertainties that surround it. First and foremost are uncertainties in future GHG policy, which is one of the main drivers in the use of renewable energy. Demand for renewable energy is highly dependent upon the design of such policies, and what these policies will look like is some developed nations as well as developing nations is still unknown.

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 edge relative to other renewable sources of energy. This edge, however, might not become evident in trends until 2030 or sometime thereafter.

Use of Abatement Systems

Emissions estimated in these projections do not explicitly consider PFC abatement. Abatement may occur when point of use (POU) abatement systems are used at a manufacturing facility for PFCs. Additionally all NF_3 used during chamber cleaning passes through required silane abatement systems for safety purposes, which are capable without modification of abating NF_3 and more capable with some modification. Emission estimates will be 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.

Table C-10 presents historical and projected emissions for all countries for this source for the analysis.

7.2.10 Other Industrial Processes Sources (CH_4, N_2O)

Historical emission estimates for the "Other Industry Sources" emissions category are based on UNFCCC-reported data. Projected emissions are assumed to remain constant at the value for the last reported year. Similarly, values before the first reported year are assumed to equal that year's value and values between two reported values are calculated using a linear interpolation. Emissions were not estimated for countries that did not report emissions in any year.

Table C-11 and Table C-12 present historical emission estimates and projections for all countries.

7.3 Agriculture

7.3.1 Agricultural Soils (N_2O)

If country-reported estimates were not available, EPA used the IPCC Tier 1 methodology to estimate emissions. EPA estimated the following six components of N_2O emissions from agricultural soils:

- Direct emissions from commercial synthetic fertilizer application
- Indirect emissions from commercial synthetic fertilizer application
- Direct emissions from the incorporation of crop residues
- Indirect emissions from the incorporation of crop residues
- Direct emissions from manure (pasture, range and paddock and all applied manure)
- Indirect emissions from manure

This section describes the methodology used to estimate N_2O emissions from agricultural soils, and is arranged by commercial fertilizer application, crop residues, and manure (including pasture, range and paddock and all applied manure).

Direct and Indirect Emissions from Commercial Synthetic Fertilizer Application

Historical Activity Data

EPA obtained commercial synthetic fertilizer consumption data from the International Fertilizer Industry Association (IFA) database of fertilizer statistics, known as IFADATA (IFA, 2010), and from the Food and Agriculture Organization of the United Nations (FAO) database of agricultural statistics, known as FAOSTAT (FAO, 2010). IFA data was the preferred source of activity data, and where IFA data were unavailable, FAO data were used. One of these activity data sources was available for most countries from 1990 through 2005. Specifically, EPA used the consumption of nitrogenous fertilizers data, reported in metric tons of N[43] (FAO) or thousand metric tons of N (IFA). EPA used the following assumptions for countries with incomplete data:

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 2005 were available from IFA, but data for Eritrea were not. To estimate the fertilizer consumption of Eritrea in 1990, EPA determined the relative ratio of the fertilizer consumption of the current Eritrea and Ethiopia in 1993. This ratio (two percent for fertilizer consumption) was then applied to the fertilizer consumption of Ethiopia PDR to estimate the fertilizer consumption of Eritrea for 1990. This method assumes 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 previously been the case. The distribution of fertilizer

[43] In the FAO online database, fertilizer data appear to be reported in metric tons, but data are actually reported in metric tons of N. This was corroborated by paper copies of the FAO statistics.

consumption between these two countries in 2000 was assumed to be the same for 1990 and 1995. Consequently, Belgium-Luxembourg consumption data 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 data 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 data in 1990 was allocated between the Czech and Slovak Republics by their relative percentages in 1993.

IFA reported data for former Soviet Union (FSU) states dating back to 1990 (before the break-up 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 are 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 Benin, Oman, and United Arab Emirates for 2005. In addition, the entire FAO time series for Bahrain and Samoa were 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.

Projected Activity Data

EPA estimated the growth rate of fertilizer consumption from 2010 to 2030 by using the regional N fertilizer consumption projections available from Tenkorang & Lowenberg-DeBoer (2008). This publication provided regional fertilizer use for 2005, 2015, and 2030, and EPA interpolated fertilizer use for 2010, 2020, and 2025. The consumption projections were then used to calculate average annual growth rates for the five-year increments between 2005 and 2030, which in turn were used to project fertilizer use by country. Countries were assigned to regions based on Annex I of Tenkorang & Lowenberg-DeBoer (2008).

Historical and Projected Emissions

As recommended in the *2006 IPCC Guidelines* (IPCC, 2006) EPA assumed that one percent of all nitrogen from fertilizer consumption is directly emitted as N_2O. Therefore, direct emissions were calculated as follows:

$$\textit{Direct emissions from synthetic fertilizer (Gg } N_2O) = F_{SN} \times EF_1 \times 44/28$$

Where:

F_{SN} = the annual amount of synthetic fertilizer N applied to soils (Gg N)

EF_1 = emission factor (equal to 0.01 Gg N_2O-N/Gg N input)

44/28 = conversion of N_2O-N to N_2O

EPA also followed the IPCC (2006) Tier 1 methodology for calculating indirect emissions from synthetic fertilizer consumption, using the following equation:

$$\textit{Indirect emissions from synthetic fertilizer (Gg } N_2O) = [(F_{SN} \times Frac_{GASF} \times EF_4) + (F_{SN} \times Frac_{leach} \times EF_5)] \times 44/28$$

Where:

F_{SN} = annual amount of synthetic fertilizer N applied to soils (Gg N)

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (equal to 0.10 Gg N volatilized/Gg N applied)

EF_4 = emission factor for N_2O emissions from N volatilization (equal to 0.01 Gg N_2O-N/(Gg NH3-N + NOx-N volatilized))

$Frac_{leach}$ = N lost from leaching and runoff (equal to 0.30 Gg N/Gg N applied)

EF_5 = emission factor for N_2O emissions from N leaching and runoff (equal to 0.0075 Gg N_2O-N/Gg N leached or runoff)

44/28 = conversion of N_2O-N to N_2O

Direct and Indirect Emissions from the Incorporation of Crop Residues

Residues from crops are typically incorporated into soils. Incorporation of crop residues directly adds nitrogen to the soil, resulting in an increase in N_2O emissions.

Historical Activity Data

FAO provided historical production and acreage statistics for the following major crops (residues of which are typically incorporated into soils): barley, maize, pulses,[44] rice, sorghum, soybeans, and wheat. Historical production and area data for these crops were available for most countries for 1990 through 2005 (FAO, 2010). For countries where data were not available, EPA assumed zero production. For countries without complete data, EPA used the following assumptions:

The former Soviet Union (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 fertilizer consumption among the FSU countries in 1993 was assumed to be the same for 1990. Consequently, Soviet consumption data in 1990 was 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 fertilizer consumption among the former Yugoslav countries in 1995 was assumed to be the same for 1990. Consequently, Yugoslavia consumption data 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).

[44] Pulses include lentils, dry beans, dry broad beans, dry horse beans, chickpeas, and pulses not elsewhere specified.

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 data in 1990 was allocated between the Czech and Slovak Republics by their relative percentages in 1993.

Ethiopia and Eritrea before 1993. In 1993, the People's Democratic Republic of Ethiopia (Ethiopia PDR) divided into Ethiopia and Eritrea. The distribution of fertilizer consumption between these two countries in 1993 was assumed to be the same for 1990. Consequently, Ethiopia PDR consumption data in 1990 was allocated between Ethiopia and Eritrea by their relative percentages in 1993.

Belgium-Luxembourg before 2000. In 2000, Belgium and Luxembourg began reporting separately to FAO, rather than together, as had previously been the case. 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 data in 1990 and 1995 was allocated between Belgium and Luxembourg by their relative percentages in 2000.

Projected Activity Data

EPA estimated the growth rate of crop area and production for 2010 to 2030 by using the country and regional crop area and production projections available from FAPRI (2010). Projected crop production and area data through the 2019/2020 agricultural year were available from FAPRI for all crops except pulses (projections for rice were available through 2018/2019). For pulses, EPA calculated and applied an average crop growth rate for all other crops. Projected data were available for world regions for all key countries by crop, and for "Rest of World." For example, country-specific crop data were available for Viet Nam for rice, since it is a major rice producing country, but Viet Nam country-specific data were not available for soybeans, since it is not a major soybean producer. For soybeans, Viet Nam was grouped with "Rest of World." For barley, maize, and wheat, "rest of [region]" data were available for countries not specified.

These area and production projections were used to calculate average annual growth rates for the five-year increments between 2005 and 2030. EPA used the 2015 to 2020 growth rate for the 2020 to 2025 and 2025 to 2030 periods. For rice, the 2015 to 2020 growth rate was based on data from 2015 through 2019. For countries for which specific data were unavailable, EPA used the five-year growth rates for the relevant region or "Rest of World." EPA then used the growth rates to project crop area and production by country.

Historical and Projected Emissions

EPA used IPCC (2006) Tier 1 methodology to estimate emissions from crop residues. The direct emissions calculation used the following equation:

$$\textit{Direct emissions from crop residues (Gg } N_2O) = F_{CR} \times EF_1 \times 44/28 \times 10^6$$

Where:

F_{CR}	= the annual amount of N in crop residues and forage/pasture renewal (kg N)
EF_1	= emission factor,(equal to 0.01 kg N_2O-N/kg N input)
$44/28$	= conversion of N_2O -N to N_2O

10^6 = conversion from kg to Gg

Indirect N_2O emissions from crop residues used the following calculation:

$$\textit{Indirect emissions from crop residues (Gg } N_2O) = F_{CR} \times Frac_{leach} \times EF_3 \times 44/28 \times 10^6$$

Where:

F_{CR} = the annual amount of N in crop residues and forage/pasture renewal (kg N)

$Frac_{leach}$ = N lost from leaching and runoff (equal to 0.30 kg N/kg N applied)

EF_3 = emission factor for N_2O emissions from N leaching and runoff (equal to 0.0075 kg N_2O-N/kg N leached or runoff)

$44/28$ = conversion of N_2O -N to N_2O

10^6 = conversion from kg to Gg

N additions to soils from crop residues depend on the crop type and yield, since different crop types have different N contents and different amounts of residue typically left in the soil. The equation for F_{CR} is:

$$F_{CR}\,(Gg\ N_2O) = \sum (Yield\ Fresh_T \times DRY_T \times S_T + I_T) \times Area_T \times (N_{ag(T)} + R_{bg\text{-}BIO\ (T)} \times N_{bg(T)})$$

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} = N content of above-ground residues (kg N/kg dry matter)

$R_{bg\text{-}BIO}$ = ratio of belowground residues to above ground biomass

N_{bg} = N content of below-ground residues (kg N/kg dry matter)

EPA used the crop residue factors by crop type shown in Table 11.2 in the *2006 IPCC Guidelines* (IPCC, 2006). If a default factor was not available for a particular crop, EPA used a proxy. N_{bg} for rice and $R_{bg\text{-}BIO}$ 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)

Direct N_2O 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 (PRP) by grazing livestock.

Historical Activity Data

EPA obtained animal population data for 1990, 1995, 2000, and 2005 through 2008 from FAO (2010). Populations of non-dairy cattle are obtained by subtracting FAO dairy cattle populations from FAO total cattle populations. In 1990, animal population data were not available for certain countries that were formed after the breakup of the Former Soviet Union (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, EPA determined the percent contribution of each country to its regional total using 1995 (1993 for Czechoslovakia) or 2000 animal population data. 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).

Projected Activity Data

EPA projected emissions from 2010-2030 based on livestock product growth rates developed by the International Food Policy Research Institute's (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (IFPRI, 2009).[45] The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, and milk for the years 2005 through 2030, in five year increments. These estimates are used to proxy average annual growth rates for the livestock species, non-dairy cattle, swine, sheep, and dairy cattle, respectively. For the remaining livestock types, the average population growth rate from 2005 through 2008 in the FAO data was used to project population growth through 2030.[46]

Starting with the historical year 2005 FAO animal population statistics, growth rates were applied to calculate projected populations for 2010, 2015, 2020, 2025, 2030, and 2035 for each livestock species.

Historical and Projected Emissions

EPA assigned countries to regions (Africa, Asia, Eastern Europe, Indian Subcontinent, Latin America, Middle East, North America, Oceania, and Western Europe) and development categories (developed, developing). EPA then used IPCC default nitrogen excretion rates by region and

[45] 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.

[46] Basing livestock population growth on the 2005 – 2008 historical trends led to unrealistically high growth rates in some countries that have experienced large livestock increases in recent years. In countries where the growth between 2008 and 2035 was greater than 200 percent, the trend was adjusted to draw on a longer historical period. Where possible, the period used was 1990 – 2008; however, in some cases, a shorter period was necessary in order to keep growth as close as possible to the range considered reasonable (i.e., 200 percent or less).

development category to estimate N excretion per head by country for each animal type, based on the country's region and development category (IPCC, 2006).

EPA then used the IPCC guidance methodology on "Coordination with reporting for N_2O emissions from managed soils," found in Section 10.5.4 of the *2006 IPCC Guidelines*, to determine the amount of N that remains in manure following management in manure management systems. The amount of N remaining corresponds to the amount available for application to agricultural soils. Using IPCC Equation 10.34, EPA estimated managed manure N available for application to managed soils as follows:

Where:

N_{MMS_Avb} = amount of managed manure nitrogen available for application to managed soils or for feed, fuel, or construction purposes (kg N yr^{-1})

$N_{(T)}$ = number of head of livestock species/category T in the country

$Nex_{(T)}$ = annual average N excretion per animal of species/category T in the country (kg N $animal^{-1}$ 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)

$Frac_{LossMS}$ = 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 MMS if known organic bedding usage) (kg N $animal^{-1}$ yr^{-1}).

S = manure management system

T = species/category of livestock

Uncertainties

The greatest uncertainties are associated with the completeness of the activity data used to derive the emission estimates. Emissions from fertilizers are estimated from only synthetic fertilizer use. In reality, organic fertilizers (other than the estimated manure and crop residues) also contribute to N_2O 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 N_2O 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 using 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 N was not considered. The "other" category for manure management is a large unknown—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, asymbiotic fixation of soil nitrogen, and mineralization of soil organic matter are not calculated or included in these estimates. 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 2030, and so projections from earlier periods are used. Additionally, in some cases projections are on a regional level, not a country-specific level and using regional projections increases uncertainty.

Table D-2 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.3.2 Enteric Fermentation (CH_4)

The basic equation to estimate emissions from enteric fermentation is as follows:

$$\textit{Emission Factor (kg/head/yr)} \times \textit{Animal Population (head)} \,/\, (10^6\ \textit{kg/Gg}) = \textit{Emissions (Gg/yr)}$$

The default emission factors are taken from the IPCC Guidelines (IPCC, 2006) and the animal population data were obtained from the Food and Agriculture Organization (FAO, 2010). The primary driver for determining CH_4 emissions from enteric fermentation was animal population. It was assumed that the animal characteristics upon which the default emission factors are based do not change significantly over time.

Historical Emissions

If reported estimates were not available, EPA used the IPCC Tier 1 methodology for each country for which FAO animal population data were available. If reported emissions were available only for a portion of the timeframe, emissions were interpolated using the available data in conjunction with the growth rate associated with the estimated Tier 1 emissions calculated for the country.

Activity Data

- EPA obtained 1990, 1995, 2000, and 2005 through 2008 animal population data from FAO (2010). Populations of non-dairy cattle were calculated by subtracting FAO dairy cattle populations from FAO total cattle populations. The FAO population data is further modified in instances where country data was 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 Former Soviet Union (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, EPA determined the percent contribution of each country to

its regional total using 1995 (1993 for Czechoslovakia) or 2000 animal population data. EPA then applied these percentages to estimate 1990 and/or 1995 animal population for these countries.

Emission Factors

- Tier 1 default emission factors from the 2006 IPCC Guidelines were used in the calculated emissions (IPCC, 2006). 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 non-dairy cattle, enteric fermentation emission factors for world regions were used, with factors assigned to countries based on the region in which they are located.

Projected Emissions

Activity Data

- EPA used reported estimates for 2010, 2015, 2020, 2025, 2030, and 2035 if available through the UNFCCC flexible query system (UNFCCC, 2012). If projections were not available, EPA projected emissions from 2005-2035 based on livestock product growth rates developed by the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (IFPRI, 2009).[47] The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, and milk for the years 2005 through 2035, in five year increments. These estimates were used to proxy average annual growth rates for the livestock species, non-dairy cattle, swine, sheep, and dairy cattle, respectively. For the remaining livestock types, the average population growth rate from 2005-2008 in the FAO data were applied.[48]
- The growth rates described above were applied to the 2005 FAO animal populations to calculate projected populations for 2010, 2015, 2020, 2025, 2030, and 2035 for each livestock species.

Emission Factors

- Emission factors used for calculating projections were the same as those described above for the historical time series calculations.

Uncertainties

The greatest uncertainties are associated with the use of default emission factors due to 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 since there is a lack of information on potential changes in the quality, quantity, and type of feed that could affect emissions in projected years. Also, the impacts of world markets and consumption patterns on

[47] 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.

[48] Basing livestock population growth on the 2005 – 2008 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 2008 and 2035 was greater than 200 percent, the trend was adjusted to draw on a longer historical period. Where possible, the period used was 1990 – 2008; however, in some cases, a shorter period was necessary in order to keep growth as close as possible to the range considered reasonable (i.e., 200 percent or less).

national livestock production patterns are often difficult to predict, further increasing the uncertainty of projected emissions from this source.

Table D-3 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.3.3 Rice Cultivation (CH_4)

The 2006 IPCC Guidelines (IPCC, 2006) provides the following overall equation for the calculation of CH_4 emissions from rice production:

Where:

$EF_{i,j,k}$	= a daily emission factor for *i, j,* and *k* conditions (kg CH_4 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 CH_4 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 IPCC Guidelines instruct countries to first obtain a baseline emission factor (EF_c) for continuously flooded fields without organic amendments. Different scaling factors are then applied to this seasonally integrated emission factor to obtain an adjusted seasonally integrated emission factor for the harvested area as follows:

$$EF_i = EF_c * SF_w * SF_o * SF_s$$

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.

Historical Emissions

If no estimates were available, EPA used the IPCC Tier 1 methodology for each country/region, as detailed below:

Activity Data

- EPA obtained data on area harvested for rice cultivation from 1990 through 2005 (FAO, 2010). If the harvested area was not available through FAO statistics, EPA assumed that the country does not grow rice.
- EPA obtained information on type of water management regime (irrigated, rainfed lowland, upland, or deepwater) from the International Rice Research Institute (IRRI, 2009).
- EPA obtained information on the length of the rice-growing season in each country (IRRI, 2009).

Emission Factors

Country-applicable daily emission factors were developed for each of the five main water management types: irrigated, rainfed lowland, upland, or deepwater. The starting point (baseline) emission factor (1.3 kg CH_4/ha-day) obtained from IPCC Guidelines (IPCC, 2006) assumes fields with no flooding for less than 180 days prior to rice cultivation, and continuously flooded during rice cultivation without organic amendments. Scaling factors from IPCC Guidelines (IPCC, 2006) are then applied to adjust the starting point emission factor for each of the other water regimes. The scaling factors 0.78, 0.28, 0.31, and 0, are used for irrigated, regular rainfed (lowland), deepwater, and upland, respectively. A scaling factor of 1.22 was used for all water regimes except upland cultivation.

- 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.
- 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.
  - Nepal's emission factor was applied to Bhutan.
  - Pakistan's emission factor was applied Afghanistan.
- Irrigated Land: Due to limited information, EPA assumed that all irrigated land is continuously flooded with no aeration. This assumption is conservative and could lead to overestimates in emissions.

Season Lengths

Country-applicable season lengths were based on IRRI data (IRRI, 2009, Appendix Table 4). 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 following assumptions were made:

- EPA assumed that a single month given (e.g., March, rather than a range, March-April) refers 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.
- EPA assumes that a range of months refers 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"), EPA added the season lengths. For countries with early and late seasons, EPA used the longer of the two seasons. For countries where IRRI identifies different rice-growing regions, EPA averaged the regions.
- For some countries where FAO indicated that rice is grown, no season length data were available, and for some countries the available data was problematic (e.g. planting dates overlapped with harvest dates). In both these cases, countries in the same region deemed to have similar climates or rice-growing schemes were used as proxies. Table 7-15 displays the country season lengths that were used as proxies.

Table 7-15: Growing Season Length Proxies

Proxy Country (Season Length)	Proxy Country Applied To:
Bulgaria	Macedonia
Democratic Republic of Congo	Angola
Dominican Republic	Jamaica, Saint Vincent and the Grenadines.
Guinea	Guinea-Bissau
Indonesia	Timor-Leste
Madagascar	Comoros
Malaysia	Brunei Darussalam
Mozambique	South Africa, Swaziland, Zambia, Zimbabwe
Nepal	Bhutan
Nicaragua	Costa Rica
Pakistan	Afghanistan
Solomon Islands	Fiji, Micronesia, Papua New Guinea
Uganda	Kenya

Emissions

- EPA multiplied area harvested for 1990, 1995, 2000, and 2005 by the combined final daily emission factor and by the season length.

If reported emissions or FAO production data were not available, EPA assumed zero emissions from this source.

Projected Emissions

If projections were not available, EPA used the following methodology to project emission estimates:

Activity Data

- Projected rice area harvested data for selected countries through 2018/2019 were available from the Food and Agriculture Policy Research Institute (FAPRI, 2010). EPA calculated growth rates for the periods 2005 through 2010, 2010 through 2015, and 2015 through 2020 (using the 2018/2019 data as a proxy for 2020 data). EPA assumed that the growth rate from 2015 through 2020 applied through 2030.
- For countries where projected area data were not available, EPA used the "Rest-of-World" area growth rates from the same FAPRI report (FAPRI, 2010).

Emissions

- EPA applied the five-year area growth rates to the historical emissions attributed to rice cultivation to develop projections at five-year intervals.

Uncertainties

Significant uncertainties exist in the CH_4 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). There were many countries where water regime information was not available, 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 flooding and aeration in irrigated areas, so EPA had to develop assumptions based on known country conditions.

Also, no scaling adjustment was made to account for organic amendments, due to 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, as many assumptions were made (detailed above) to turn a rough estimate of month ranges into a specific number of days. In addition, a number of countries were proxied due to lack of data, and these proxies for season length might not be accurate. Lastly, since projections beyond 2020 were based on growth rates from 2015 through 2020, increased uncertainty is introduced through these assumptions.

Table D-4 presents historical emissions and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.3.4 Manure Management (CH_4, N_2O)

Many developing countries report estimates of CH_4 emissions and some countries also report N_2O emissions for manure management; however, there is generally less coverage of N_2O emissions in the published inventory data.

The basic equation to estimate emissions from manure management is as follows:

$$\textit{Emission Factor (kg/head/yr)} \times \textit{Animal Population (head)} / (10^6\ \textit{kg/Gg}) = \textit{Emissions (Gg/yr)}$$

The default manure management emission factors are either taken directly or derived from the data provided in the 2006 IPCC Guidelines (IPCC 2006) and livestock population data are obtained from the Food and Agriculture Organization (FAO, 2010). The primary driver for determining CH_4 emissions from enteric fermentation is animal population, assuming that waste management and animal characteristics do not change significantly over time.

Historical Emissions

If country-reported estimates were not available, EPA used the IPCC Tier 1 methodology for each country where FAO animal population data were available (IPCC, 2006). 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.

Activity Data

- EPA obtained 1990, 1995, 2000, and 2005 through 2008 animal population data from FAO (2010). Populations of non-dairy cattle were estimated by subtracting FAO dairy cattle estimates from FAO total cattle estimates. The FAO population data is further modified in instances where country data was aggregated for part of the time series. For example, in 1990, animal population data are not available for certain countries that have since been established after the breakup of the Former Soviet Union (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, EPA determined the percent contribution of each country to their regional total using 1995 (1993 for Czechoslovakia) or 2000 animal population data. EPA then applied these percentages to estimate 1990 and/or 1995 animal populations for these countries.

Emission Factors

- For sheep, goats, camels and other camelids, horses, mules and asses, and poultry, CH_4 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).
- For cattle, swine and buffalo, CH_4 emission factors from the 2006 IPCC Guidelines were used, and were selected based on region and average annual temperature (provided in increments of one degree Celsius) for the country.
- According to IPCC (2006) Tier 1 default assumptions, N_2O manure emission factors for animal categories other than cattle, buffalo, swine and poultry is assumed to be managed in pasture and grazing operations and is therefore not included in the manure management estimates. Therefore manure management emissions from these animal types were assumed to be zero and are estimated under N_2O from agriculturally managed soils.
- For cattle, buffalo, swine, and poultry all default data was obtained from the 2006 IPCC Guidelines (IPCC, 2006). Nitrogen (N) excretion rates (kg N per 1,000 kg animal mass) were obtained by animal type and region, and were used in conjunction with typical animal mass estimates (in kg, available by animal type and region for cattle, swine, and

buffalo and by developed or developing country designation for poultry) to calculate an N excretion rate per head per year for each animal type and region, and also by developed or developing country designation for poultry. The N 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.

- EPA estimated climate type for most countries using data from the Global Historical Climatology Network, which is published by the National Climatic Data Center and contains annual average temperatures for most country's capital/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, EPA assumes that 100 percent of the animal populations are located in a climate defined by the average temperature of the country capital.

Projected Emissions

Activity Data

- EPA used reported estimates for 2010, 2015, 2020, 2025, and 2030 if available through National Communications (UNFCCC, 2012). If projections were not available, EPA projected emission estimates from 2005 to 2030 based on livestock product growth rates developed by the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (IFPRI, 2009).[49] The IMPACT model projects growth rates by country for the demand of beef, pork, lamb, and milk for the years 2005 through 2035, in five year increments. These estimates are used to proxy average annual growth rates for the livestock species, non-dairy cattle, swine, sheep, and dairy cattle, respectively. For the remaining livestock types, the average population growth rate from 2005-2008 in the FAO data were applied. [50]
- The growth rates described above were applied to the 2005 FAO animal populations to calculate projected populations for 2010, 2015, 2020, 2025, and 2030 for each livestock species.

Emission Factors

- Projected emission factors were the same as those described above for the historical time series calculations.

Uncertainties

The default emission factors represent the greatest source of uncertainty due to the lack of information on country-specific manure management systems and the geographic concentration of

[49] 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.

[50] Basing livestock population growth on the 2005 – 2008 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 2008 and 2035 was greater than 200 percent, the trend was adjusted to draw on a longer historical period. Where possible, the period used was 1990 – 2008; however, in some cases, a shorter period was necessary in order to keep growth as close as possible to the range considered reasonable (i.e., 200 percent or less).

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 impacts of 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.

Table D-5 and Table D-6 present historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.3.5 Other Agriculture Sources (CH_4, N_2O)

The sources included in this category are prescribed burning of savannas, field burning of agricultural residues, and open burning from forest clearing. This category also includes small amounts of country-reported emissions data on CH_4 from agricultural soils. However, biomass burning constitutes the majority of emissions for this source.

Emissions from biomass burning were obtained from the Emission Database for Global Atmospheric Research (EDGAR), Version 4.0 (EC-JRC, 2009). EDGAR contains historical emissions data for 1990 to 2005. Similar to the remaining "Other" sources, 2010 through 2035 emission estimates are set equal to the 2005 estimates. EDGAR contains historical data for the following biomass burning sources:

- Savanna Burning (IPCC Category 4E)
- Agricultural Waste Burning (IPCC Category 4F)
- Forest Fires (IPCC Category 5A)
- Grassland Fires (IPCC Category 5C)
- Forest Fires – Post Burn Decay (IPCC Category 5F2)

Table D-7 and Table D-8 present historical emission estimates and projections for all countries.

7.4 Waste

7.4.1 Landfilling of Solid Waste (CH_4)

If country-reported estimates were not available or country-reported activity data were insufficient, EPA used the *2006 IPCC Guidelines for National GHG Inventories* Tier 1 methodology and the associated simple spreadsheet model (IPCC Waste Model) to estimate emissions (IPCC, 2006).[51] The emission estimates for this source, calculated in the IPCC Waste Model, are based on the IPCC First Order Decay (FOD) method primarily using default activity data and default parameters. As per the *2006 IPCC Guidelines for National GHG Inventories*, this method assumes that the degradable organic carbon (DOC) in waste decays slowly throughout a few decades releasing CH_4 over time. This updated IPCC 2006 Tier 1 methodology, used in cases where country-reported data was missing, is different from the IPCC 1996 Tier 1 methodology used in the 2006 GER report because it includes

[51] Due to modeling limitations in the IPCC Waste Model and data availability issues, EPA was unable to model certain drivers such as cover material characteristics, seasonal fluctuation in CH_4 oxidation rates, and landfill gas recovery.

the temporal dimension for CH_4 emissions associated with the slow decay of organic matter over time.

CH_4 emissions from Solid Waste Disposal Sites (SWDS) for a single year can be estimated using the Tier 1 equation below from the 2006 IPCC Guidelines. CH_4 is generated due to degradation of organic material under anaerobic conditions. Part of the CH_4 generated is oxidized or can be recovered for energy or flaring and as a result, the CH_4 actually emitted will be less than the amount generated.

$$CH_4 Emissions_t = \left[\sum_x CH_4 generated_{x,T} - R_T \right] * (1 - OX_T)$$

Where:

$CH_4 generated_{x,T}$	=	*CH_4 generated from decomposable material x in year T*
CH_4 *Emissions* $_T$	=	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)

The IPCC Waste Model utilizes the FOD method to calculate CH_4 generated based on the degradable organic carbon (DOC) amounts in waste disposed each year which decompose under anaerobic conditions. For further explanation regarding the methodology, please refer to Chapter 3, "Solid Waste Disposal" of the *2006 IPCC Guidelines for National GHG Inventories* (IPCC, 2006).

Historical Emissions

Activity Data

If a portion of the historical time series was reported, EPA used the following to interpolate, extrapolate, and/or backcast emission estimates to estimate the entire time series from 1990 to 2007:

- Total population[52] data were obtained from the *U.S. Census International Database* (Census, 2009) and used to estimate historical landfill CH_4 emissions by applying population growth rates to the reported emission estimates.[53]

If country-reported data was not available for the entire historical and projected time series, the IPCC 2006 Waste Model was run for these countries to calculate both historical and projected emissions from 1950 to 2030. EPA used the following activity data as inputs into the IPCC Waste Model:

[52] 2006 IPCC Guidelines state that historical urban population data can be used as a proxy to estimate MSW disposal, and historical total population data can be used when urban population data is not available. (Vol. 5, Ch-3, pp. 3.12)

[53] Proxy populations were assumed based on similar size or geographical regions for countries that did not provide population data in the US Census database.

- Population data obtained from the *U.S. Census International Database* (Census, 2009) were used to estimate and project MSW generation.
- GDP data in Real 2005 Dollars obtained from U.S. Department of Agriculture (USDA, 2009) were used to estimate and project industrial waste generation.[54]
- IPCC Waste model defaults were used in most cases, such as "waste per capita" and the composition percentages of household waste going to SWDSs.
- Climate zones were selected for the "CH_4 generation rate" input in the IPCC waste Model using *IPCC 2003 Good Practice Guidance for LULUCF* (Section 3.1) (IPCC, 2003) and relevant default values were used for the selected region.
- An industrial waste generation proxy country was selected to assume a "waste generation rate" if default values were not available. This selection was performed according to the guidance in Section 2.2.3 of *2006 IPCC Guidelines for National GHG Inventories* (IPCC, 2006). A proxy country was selected, based on similar circumstances, from a list of countries provided in Table 2.2 (Industrial Waste generation for Selected Countries) of section 2.2.3.
- Based on *2006 IPCC Guidelines for National GHG Inventories* (Section 2.2.3), the percent of industrial waste generated and sent to landfills (% to SWDS) was assumed to be the same as the IPCC regional default for percent of MSW sent to landfills.

Emission Factors

The IPCC 2006 Waste Model was used to calculate emissions for countries that did not report historical emission estimates (mainly non-Annex I countries). The following assumptions were made with respect to emission factors:

- DOC (mass of degradable organic carbon), DOC_f (fraction of DOC dissimilated), k (CH_4 generation rate), were based on IPCC default values (IPCC, 2006). The values are primarily based on the selected climate zone and geographic region.
- Oxidation (OX) and recovery (R) were assumed to equal zero.[55] However, Annex-I countries that report emissions may be assuming non-zero numbers for these rates.
- IPCC default values were used for estimated distribution of site types (managed or unmanaged, deep or shallow, and uncategorized) and distribution of waste by site type.

Projected Emissions

If projections from National Communications were not available, EPA used the following methodology to project emission estimates:

[54] Proxy GDP was assumed based on similar size or geographical regions for countries that did not provide GDP data in the USDA data.

[55] EPA recognizes that programs such as the Landfill Methane Outreach Program (LMOP) are encouraging landfill gas recovery and use for energy in Non-Annex 1 countries leading to significant emission reductions. EPA will consider incorporating this data for future revisions.

Activity Data

If a portion of the projected time series was reported, EPA used the following to project emission estimates from 2007 to 2030:

- EPA interpolated between projected emissions values and extrapolated out to 2030 based on the last 5-year interval projections as indicated through National Communications.

If country-reported projected data were not available and a historical emission estimate was reported, EPA used the following activity data to project emission estimates:

- Population data obtained from the *U.S. Census International Database* (Census, 2009) were used to estimate and project landfill CH_4 emissions by applying population growth rates to the reported emission estimates.[56]
- If country-reported data were not available for the entire historical and projected time series, the IPCC 2006 Waste Model (IPCC, 2006) was run for these countries to calculate both historical and projected emissions from 1950 to 2030. The assumptions regarding inputs into the model are outlined in the historical emissions section above.

Emission Factors

- The IPCC 2006 Waste Model (IPCC, 2006) was used to calculate emissions for countries that did not report historical emission estimates. The assumptions regarding emission factor inputs into the model are outlined in the historical emissions section above.

Uncertainties

Uncertainties in the estimation of CH_4 emissions from landfills are due in large part to the lack of one or more country-specific values for the following parameters: MSW generation per capita, percent to MSW, percent to managed landfills, DOC fractions, oxidation factors, and recovery. Also, while the drivers for projections were selected to capture future trends in the movement of waste to MSW landfills, there is considerable uncertainty, particularly in the developing regions of the world, in predicting landfill utilization. Finally, although the methodology for projecting landfilling CH_4 emissions from waste disposal using population growth is acceptable as per the IPCC 2006 Guidelines for a Tier 1 approach, waste disposal is likely influenced by multiple drivers including economic and population growth.

Table E-2 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.4.2 Wastewater (CH_4)

The basic equation to estimate emissions from wastewater is as follows:

$$CH_4 Emissions = \left[\sum_{i,j} \left(U_i \times T_{i,j} \times EF_j \right) \right] TOW$$

[56] Proxy populations were assumed based on similar size or geographical regions for countries that did not provide population data in the US Census database.

Where:

CH_4 *Emissions*	= CH_4 emissions per year, kg CH_4/yr
TOW	= total organics in wastewater per year, kg BOD/yr
U_i	= fraction of population in income group *i*
$T_{i,j}$	= degree of utilization of treatment/discharge pathway or system, *j*, for each income group fraction, *i*
i	= income group: rural, urban high income, urban low income
j	= each treatment, discharge pathway or system
EF_j	= emission factor for treatment/discharge pathway or system, *j,* kg CH_4/kg BOD

The emission factors are a product of maximum CH_4 producing capacity (kg CH_4/kg biochemical oxygen demand (BOD)) and a CH_4 correction factor specific to each treatment or discharge pathway or system. The maximum CH_4 producing capacity used in this analysis is 0.6 kg CH_4/kg BOD, which is the default value in the 2006 IPCC guidelines. The above equation differs from the 2006 IPCC Guidelines in that estimates for organics removed as sludge and CH_4 recovery were not feasible to estimate by country on a global scale.

Total organics in wastewater is calculated by multiplying population by biochemical oxygen demand (BOD) per person.

Historical Emissions

Historical estimates were based on emissions data obtained from the UNFCCC flexible query system where data were available from 1990 through 2009 (UNFCCC, 2012). The time series was available for most A1 countries, however gaps existed in the time series for the majority of the NA1 countries. For the remainder of the historical time series, EPA applied growth rates to the 2007 base year estimate as follows:

- When two years were reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), EPA interpolated the missing estimate (1995) using linear interpolation of the reported estimates.
- EPA applied population growth rates calculated from the U.S. Census International Data Base (Census, 2009) to the reported emission estimates to complete the historical time series of emissions.

Activity Data

- Population data were from the U.S. Census International Data Base (Census, 2009). The U.S. Census International Data Base does not provide population data for Holy See or Niue. For these countries, EPA used population estimates from the CIA World Factbook (CIA, 2010) and assumed a constant population from 1990 to 2035.
- BOD data by region/country, CH_4 generation capacity, wastewater treatment pathways by region/country, and urbanization scenarios were based on IPCC 2006 Guidelines

default factors for domestic wastewater (IPCC, 2006). The Holy See is assumed to have 100 percent of its population in Urban High conditions.

Emission Factors and Emissions

- EPA calculated CH_4 emissions from wastewater by multiplying activity data (i.e., BOD data, wastewater treatment pathways) by default Tier 1 IPCC emission factors from IPCC, 2006.
- The UNFCCC-reported emissions for South Korea decreased by 99 percent from 1990 to 2000. To address this anomaly, the emissions for South Korea are projected from the reported 1990 value using population data. The reported value for 2000 was not used.

Projected Emissions

Projected emission estimates were based on emissions data obtained from National Communications (NC), where available. Estimates for some years were available for six countries (Germany, Greece, Italy, Poland, Slovakia, and the United Kingdom). These estimates were incorporated into the time-series as follows:

- EPA projected emission estimates using NC data similar to the methodology followed to estimate historical estimates using UNFCCC data. When two years were reported such that a year requiring an estimate (e.g., 2010) occurred between the NC reported year (e.g., 2015) and the UNFCCC reported year (e.g. 2000), EPA interpolated the missing estimate (2010) using linear interpolation of the reported estimates.
- EPA applied population growth rates calculated from the U.S. Census International Data Base (Census, 2009) to the NC-reported emission estimates to complete the projected time series of emissions.
- Where NC data were not available for countries with UNFCCC reported historical emissions, historical emissions were projected using population growth rates calculated from the U.S. Census International Data Base (Census, 2009).

Activity Data

- Population data were from the U.S. Census International Data Base (Census, 2009), which provides annual population estimates through 2050. The U.S. Census International Data Base does not provide population data for Holy See or Niue. For these countries, EPA used population estimates from the CIA World Factbook (CIA, 2010) and assumed population remains constant across the time period.
- BOD data by region/country, CH_4 generation capacity, wastewater treatment pathways by region/country, and urbanization scenarios were based on 2006 IPCC Guideline default factors (IPCC, 2006). The Holy See was assumed to have 100 percent of its population in Urban High conditions.

Emission Factors and Emissions

- The emission factors used to calculate projected emissions are the same IPCC default factors used in the historical time series calculations (IPCC, 2006).

Uncertainties

Significant uncertainty exists in this methodology in that as developing countries modernize or change their domestic wastewater handling in the future, the shift to aerobic treatment will reduce

emissions. Other uncertainties exist with respect to population projections and linear interpolation projections of UNFCCC reported data for individual countries.

Table E-3 presents historical emission estimates and projections for all countries.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.4.3 Human Sewage – Domestic Wastewater (N_2O)

The basic equation to estimate N_2O emissions from human sewage is as follows:

$$N_2O\ Emissions = N_{SEWAGE} \times EF_{SEWAGE} \times 44/28$$

Where:

$N_2O_{(s)}$ = N_2O emissions from human sewage (kg N_2O/yr)

N_{SEWAGE} = Nitrogen in human sewage (kg N/yr)

EF_{SEWAGE} = Emission factor for N_2O emissions from human sewage (default = 0.005 kg N_2O-N/kg N)

The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

The nitrogen content of human sewage is calculated according to the equation below:

$$N_{SEWAGE} = P \times Protein \times F_{NPR}$$

Where:

N_{SEWAGE} = total annual amount of nitrogen in human sewage, kg N/yr

P = country population

$Protein$ = annual per capita protein consumption, kg/person/yr

F_{NPR} = fraction of nitrogen in protein (default = 0.16 kg N/kg protein)

Historical Emissions

Historical estimates were based on emissions data obtained from the UNFCCC flexible query system where data were available from 1990 through 2009 (UNFCCC, 2012). The time series was available for most A1 countries, however gaps existed in the time series for the majority of the NA1 countries. For the remainder of the historical time series EPA applied growth rates to the 2007 year estimate as follows:

- When two years were reported such that a year requiring an estimate (e.g., 1995) occurred between the reported years (e.g., 1993 and 1997), EPA interpolated the missing estimate (1995) using linear interpolation of the reported estimates.
- EPA applied population growth rates calculated from the U.S. Census International Data Base (Census, 2009) to the reported emission estimates to complete the historical time series of emissions.

Activity Data

- Population data were from the U.S. Census International Data Base (Census, 2009), which provides annual population from 1950 through 2035. The U.S. Census International Data Base does not provide population data for Holy See or Niue. For these countries, EPA used population estimations from the CIA World Factbook (CIA, 2010) and assumed population remains constant across the time period.
- Protein consumption data by country were taken from the Food and Agriculture Organization (FAO) of the 2009 United Nations Statistical Yearbook (FAO, 2009). FAO provides protein consumption values for three periods: 1994-1996, 1999-2001, and 2003-2005. These values were used for the 1995, 2000, and 2005 estimates, respectively. Protein consumption values for 1990 were assumed equal to the values for 1995.
- The 2009 FAO Statistical Yearbook did not provide protein consumption data for a number of countries. For these countries, EPA used geographically adjacent countries as a proxy for protein consumption, as indicated in Table 7-16 below.

Table 7-16: Countries Used to Estimate Protein Consumption in Countries Missing Data

Country Missing Protein Consumption Data:	Protein Consumption Assumed Equal to:
Afghanistan	Iran
Andorra	average of France and Spain
Bahrain	Saudi Arabia
Bhutan	Nepal
Cook Islands	Solomon Islands
Djibouti	Ethiopia
Equatorial Guinea	Gabon
Grenada	Trinidad and Tobago
Holy See	Italy
Iraq	Iran
Kiribati	Solomon Islands
Liechtenstein	average of Austria and Switzerland
Maldives	Sri Lanka
Marshall Islands	Solomon Islands
Micronesia (Federated States of)	Solomon Islands
Monaco	France
Montenegro	Bosnia and Herzegovina
Nauru	Solomon Islands
Niue	Solomon Islands
Oman	Saudi Arabia
Palau	Solomon Islands
Papua New Guinea	Indonesia
Qatar	Saudi Arabia
San Marino	Italy
Serbia	Bosnia and Herzegovina
Singapore	Malaysia
Tonga	Solomon Islands

Emission Factors and Emissions

- EPA calculated N_2O emissions from human sewage by multiplying activity data (i.e., protein consumption, population) by default Tier 1 IPCC factors from IPCC, 2006. These default factors include F_{NPR}, the fraction of nitrogen in protein; 44/28, the conversion of kg N_2O-N into kg N_2O; and the emission factor for N_2O emissions from human sewage.
- The 1990 UNFCCC-reported estimate for Paraguay was two orders of magnitude higher compared to other estimates by Paraguay, as well as similar countries; therefore 1990 emissions were calculated by backcasting the 1994 country-reported estimate.

Projected Emissions

Projected emission estimates were based on emissions data obtained from National Communications (NC), where available. Projections for some years were available for six countries (Germany, Greece, Ireland, Italy, Poland, and Slovakia). These estimates were incorporated into the time-series as follows:

- EPA projected emission estimates using NC data similar to the methodology followed to estimate historical estimates using UNFCCC data. When two years were reported such that a year requiring an estimate (e.g., 2010) occurred between the NC reported year (e.g., 2015) and the UNFCC reported year (e.g. 2000), EPA interpolated the missing estimate (2010) using linear interpolation of the reported estimates.
- EPA applied population growth rates calculated from the U.S. Census International Data Base (Census, 2009) to the NC-reported emission estimates to complete the projected time series of emissions.
- Where NC data were not available for countries with UNFCCC reported historical emissions, historical emissions were projected using population growth rates calculated from the U.S. Census International Data Base.

Activity Data

- Population data were from the U.S. Census International Data Base (Census, 2009), which provides annual population estimates, by country through 2050. The U.S. Census International Data Base does not provide population data for Holy See or Niue. For these countries, EPA used population estimates from the CIA World Factbook (CIA, 2010) and assumed population remains constant across the time period.
- Protein consumption data by country is taken from the Food and Agriculture Organization (FAO) of the 2009 United Nations Statistical Yearbook (FAO, 2009). Protein consumption values for 2010-2030 are assumed equal to the FAO reported values for 2003-2005.
- The 2009 FAO Statistical Yearbook did not provide protein consumption data for a number of countries. For these countries, EPA used geographically adjacent countries as a proxy for protein consumption, as indicated in Table 7-16 above.

Emission Factors and Estimates

- The emission factors used to calculate projected emissions are the same IPCC default factors used in the historical time series calculations (IPCC, 2006).

- Greece's NC-reported projections were two orders of magnitude smaller than the historical UNFCCC data indicated. Therefore, projections for Greece are calculated by forecasting UNFCCC-reported data using population growth, rather than using NC-reported data.

Uncertainties

Significant uncertainty exists in this methodology in that as developing countries modernize and change their dietary standards, an increase in protein consumption will increase emissions; this uncertainty is particularly applicable to China and India with very large populations and economic growth potential. Other uncertainties exist with respect to population projections and linear interpolation projections of UNFCCC reported data for individual countries.

Table E-4 presents historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

7.4.4 Other Waste Sources (CH_4, N_2O)

Emission estimates for the "Other Waste Sources" emissions category are based on UNFCCC-reported data. Future emissions are assumed to remain constant at the value for the last reported year. Similarly, values before the first reported year are assumed to equal that year's value and values between two reported values are calculated using a linear interpolation. No emissions are estimated for countries that did not report emissions in any year.

Table E-5 and Table E-6 present historical and projected emissions for all countries for this source.

Appendix G and Appendix H describe the methodologies and data sources used for each country.

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Appendices

Appendix A: Total Emissions by Country
Table A-1: Total Non-CO_2 Emissions by Country ($MtCO_2e$)
Table A-2: Total CH_4 Emissions by Country ($MtCO_2e$)
Table A-3: Total N_2O Emissions by Country ($MtCO_2e$)
Table A-4: Total F-GHG Emissions by Country ($MtCO_2e$)

Appendix B: Energy Sector Emissions
Table B-1: Total Non-CO_2 Emissions from the Energy Sector by Country ($MtCO_2e$)
Table B-2: CH_4 Emissions from Natural Gas and Oil Systems by Country ($MtCO_2e$)
Table B-3: CH_4 Emissions from Coal Mining Activities by Country ($MtCO_2e$)
Table B-4: CH_4 Emissions from Stationary and Mobile Combustion by Country ($MtCO_2e$)
Table B-5: N_2O Emissions from Stationary and Mobile Combustion by Country ($MtCO_2e$)
Table B-6: CH_4 Emissions from Biomass Combustion by Country ($MtCO_2e$)
Table B-7: N_2O Emissions from Biomass Combustion by Country ($MtCO_2e$)
Table B-8: CH_4 Emissions from Other Energy Sources by Country ($MtCO_2e$)
Table B-9: N_2O Emissions from Other Energy Sources by Country ($MtCO_2e$)

Appendix C: Industrial Processes Sector Emissions
Table C-1: Total Non-CO_2 Emissions from the Industrial Processes Sector by Country ($MtCO_2e$)
Table C-2: N_2O Emissions from Adipic Acid and Nitric Acid Production by Country ($MtCO_2e$)
Table C-3: HFC and PFC Emissions from Use of Substitutes for Ozone-Depleting Substances by Country ($MtCO_2e$)
Table C-4: HFC-23 Emissions from HCFC-22 Production by Country ($MtCO_2e$)
Table C-5: SF_6 Emissions from Electric Power Systems by Country ($MtCO_2e$)
Table C-6: PFC Emissions from Primary Aluminum Production by Country ($MtCO_2e$)
Table C-7: F-GHG Emissions from Semiconductor Manufacturing by Country ($MtCO_2e$)
Table C-8: SF_6 Emissions from Magnesium Manufacturing by Country ($MtCO_2e$)
Table C-9: SF_6 and PFC Emissions from Flat Panel Display Manufacturing by Country ($MtCO_2e$)
Table C-10: PFC Emissions from Photovoltaic Manufacturing by Country ($MtCO_2e$)
Table C-11: CH_4 Emissions from Other Industrial Processes Sources by Country ($MtCO_2e$)
Table C-12: N_2O Emissions from Other Industrial Processes Sources by Country ($MtCO_2e$)

Appendix D: Agriculture Sector Emissions
Table D-1: Total Non-CO_2 Emissions from the Agriculture Sector by Country ($MtCO_2e$)
Table D-2: N_2O Emissions from Agricultural Soils by Country ($MtCO_2e$)
Table D-3: CH_4 Emissions from Enteric Fermentation by Country ($MtCO_2e$)
Table D-4: CH_4 Emissions from Rice Cultivation by Country ($MtCO_2e$)
Table D-5: CH_4 Emissions from Manure Management by Country ($MtCO_2e$)
Table D-6: N_2O Emissions from Manure Management by Country ($MtCO_2e$)
Table D-7: CH_4 Emissions from Other Agricultural Sources by Country ($MtCO_2e$)
Table D-8: N_2O Emissions from Other Agricultural Sources by Country ($MtCO_2e$)

Appendix E: Waste Sector Emissions
Table E-1: Total Non-CO_2 Emissions from the Waste Sector ($MtCO_2e$)
Table E-2: CH_4 Emissions from Landfilling of Solid Waste by Country ($MtCO_2e$)
Table E-3: CH_4 Emissions from Wastewater by Country ($MtCO_2e$)
Table E-4: N_2O Emissions from Human Sewage - Domestic Wastewater by Country ($MtCO_2e$)
Table E-5: CH_4 Emissions from Other Waste Sources by Country ($MtCO_2e$)
Table E-6: N_2O Emissions from Other Waste Sources by Country ($MtCO_2e$)

Appendix F: Refrigeration and Air Conditioning (RefAC) Disaggregation

Appendix G: Methodology Applied to Develop Source Emissions
Table G-1: Methodology Applied to Develop Energy Sector Source Emissions, by Country
Table G-2: Methodology Applied to Develop Industrial Processes Sector Source Emissions, by Country
Table G-3: Methodology Applied to Develop Other Industrial Processes Sector Source Emissions, by Country
Table G-4: Methodology Applied to Develop Agriculture Sector Source Emissions, by Country
Table G-5: Methodology Applied to Develop Waste Sector Source Emissions, by Country

Appendix H: Data Sources Used to Develop Non-Country Reported Emissions Estimates

Appendix I: Future Mitigation Measures Included in Developing Non-Country-Reported Estimates

Appendix J: Regional Definitions

Appendix K: U.S. EPA Vintaging Model Framework