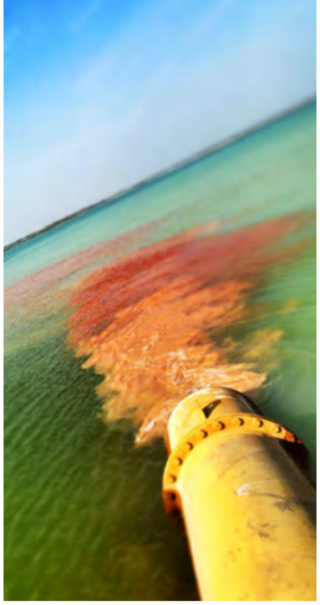

United States
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Office of Atmospheric
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Washington, DC 20005

EPA-430-R-19-010
October 2019

Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation

2015–2050

How to Obtain Copies

You can electronically download this document on the U.S. EPA's homepage at https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases.

All projections and mitigation data described in this document for the full time series 1990 through 2050, inclusive, are made available at the internet site mentioned above. In addition, the data are accessible through a data exploration tool at https://cfpub.epa.gov/ghgdata/nonco2/.

For Further Information

Contact Mr. Shaun Ragnauth, Environmental Protection Agency, (202) 343-9142, ragnauth.shaun@epa.gov, or Mr. Jameel Alsalam, Environmental Protection Agency, (202) 343–9807, alsalam.jameel@epa.gov.

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Abt Associates and ICF International conducted the emission projections analysis and authored the projections portions of the report. RTI International conducted the mitigation analysis for all sectors and authored the mitigation portions of the report.

Abt Associates, Inc.

Dan Bosoli

ICF International

Mollie Averyt
Cara Blumenthal
Rani Murali
Sabrina Andrews
Rebecca Ferenchiak
Deborah Harris
Kristen Jaglo
Megha Kedia
Robert Lanza
Lance LaTulipe
Jerry Marks
Andrew Stilson
Neha Vaingankar
Mollie Carroll
Katrin Moffroid

RTI International

Jeffrey Petrusa
Kyle Clark-Sutton
Justin Larson
Alison Bean
Robert Beach

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Keith A. Smith (University of Edinburgh)

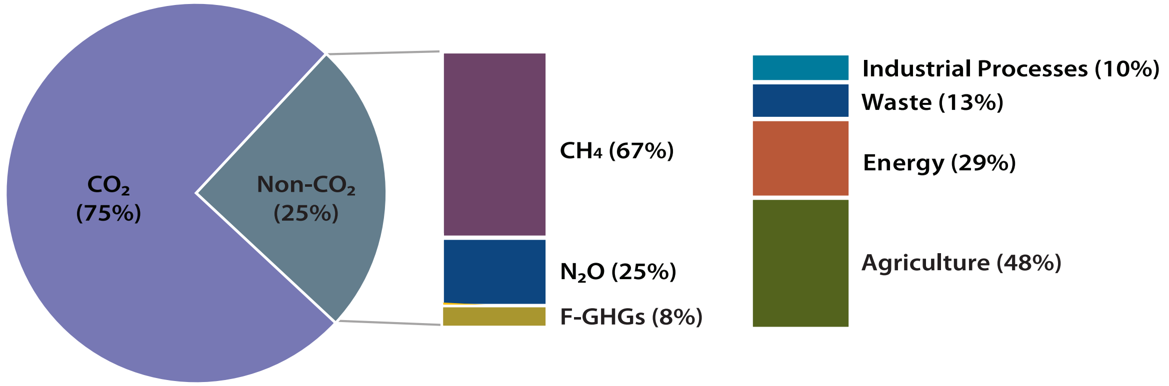
Table of Contents

Introduction

This report is the latest installment of the U.S. Environmental Protection Agency's (EPA's) non-carbon dioxide (non-CO_2) greenhouse gas (GHG) assessments and combines two long-running EPA report series: *Non-CO_2 Greenhouse Gases: International Emissions and Projections*[1,2] and *Global Mitigation of Non-CO_2 Greenhouse Gases*.[3,4] Combining the "projections" and "mitigation" reports provides an opportunity to better align these two documents and their respective uses.

This report provides a consistent and comprehensive set of (1) historical and projected estimates of emissions and (2) technical and economic mitigation estimates of non-CO_2 GHGs from anthropogenic sources for 195 countries. The analysis provides information that can be used to understand national contributions of GHG emissions, historical progress on reductions, and mitigation opportunities.

Global Non-CO_2 Emission by Gas and Sector in 2015
(Non-CO_2 GHGs = 12,010 $MtCO_2e$)



The projections were generated using a combination of country-reported inventory data supplemented with EPA-estimated calculations consistent with inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC). The mitigation estimates were generated using a bottom-up, engineering cost approach that analyzed the costs of a wide range of mitigation technologies and incorporated them into an economic tool called a marginal abatement cost (MAC) curve, which summarizes the cost and emission reductions achievable from each source.

Historical emission estimates were incorporated from country-reported data from 1990 through 2015, and emissions were projected through 2050; mitigation estimates are available for 2020 through 2050. The projections results are a "business-as-usual" (BAU) scenario with emission rates consistent with historical levels and do not include future effects of policy changes. Mitigation options represented in the MAC curves reduce emissions from the BAU scenario. Although emission and mitigation estimates are available through 2050, this report focuses on projections and mitigation estimates in the year 2030 to provide more near-term results for discussion.

The EPA estimates that global non-CO_2 GHG emissions in 2015 totaled approximately 12,010 $MtCO_2e$. When added to a global CO_2 emission estimate for 2015 of approximately 36,000 $MtCO_2e$,[5] anthropogenic non-CO_2 emissions represent 25% of the global GHG emissions emitted annually on a CO_2 equivalent basis in 2015.

Non-CO_2 GHGs

The GHGs 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 fluorinated greenhouse gases (F-GHGs) that include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Compounds covered by the Montreal Protocol are not included.

Source Categories and GHGs Included in this Report

Sector/Source	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3
Energy						
Coal mining activities	●					
Natural gas and oil systems	●					
Combustion of fossil fuels and biomass	●	●				
Industrial Processes						
Nitric and adipic acid production		●				
Electronics manufacturing[a]			●	●	●	●
Electric power systems					●	
Metals						
Primary aluminum production				●		
Magnesium manufacturing					●	
Use of substitutes for ozone-depleting substances[b]			●			
HCFC-22 production			●			
Agriculture						
Livestock						
Enteric fermentation	●					
Manure management	●					
Croplands (agricultural soils)		●				
Rice cultivation	●	●				
Waste						
Landfilling of solid waste	●					
Wastewater	●	●				

[a] Electronics manufacturing includes semiconductors, photovoltaics, and flat panel displays.
[b] Substitutes for ozone-depleting substances include uses in refrigeration and air-conditioning, solvents, foams, aerosols, and fire extinguishers.

These non-CO_2 GHGs are more potent (per unit weight) than CO_2 at trapping heat within the atmosphere. Additionally, some non-CO_2 GHGs can remain in the atmosphere for longer periods of time than CO_2. Global warming potential (GWP) is the factor that quantifies the heat-trapping potential of each GHG relative to CO_2.

Global Warming Potential Factors by Gas

Greenhouse Gas	GWP[a] Factor
CO_2	1
CH_4	25
N_2O	298
HFC-23	14,800
HFC-32	675
HFC-125	3,500
HFC-134a	1,430
HFC-143a	4,470
HFC-152a	124
HFC-227ea	3,220
HFC-236fa	9,810
HFC-4310mee	1,640
CF_4	7,390
C_2F_6	12,200
C_4F_{10}	8,860
C_6F_{14}	9,300
NF_3	17,200
SF_6	22,800

[a] 100-year time horizon.

Source: Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge, United Kingdom: Cambridge University Press.[6]

Methods Overview

General Methods

The methodologies employed to generate non-CO_2 GHG emission projections and mitigation estimates build on those used in previous reports from this series.[7,8,9,10] Updates and enhancements have been made to both the projections and mitigation methodologies for this report. A summary of the projections and mitigation methodologies, along with a discussion of enhancements and changes since the last publications, is presented in this section.

The full methodology used to develop the emission and mitigation estimates presented in this report is documented in the peer-reviewed EPA report *Global Non-CO_2 Greenhouse Gas Emission Projections & Marginal Abatement Cost Analysis: Methodology Documentation (EPA-430-R-19-012)*.

Emission Projections: Methods

The EPA prepared a complete set of non-CO_2 GHG emission estimates, regardless of available country-reported estimates, in a consistent manner across all countries to produce a global inventory.[11] To develop the estimates of historical and BAU projected emissions, the EPA used publicly available emission estimates from official nationally prepared GHG reports[12] in combination with EPA-estimated emissions consistent with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines).[13]

To project emissions, the EPA used drivers based on globally available growth rate or activity data specific to each source. Depending on available information, the projected emission estimates for each country and source are either (1) a composite of historical country-reported emissions and calculated estimates or (2) calculated estimates based on IPCC default emission factors and globally available activity data. In most cases, some country-reported data are available, so the composite approach was used. The second approach was only used when no country-reported data are available for a source category. For estimates based on the composite approach, the Tier 1 calculated emission estimates were used to determine trends through the time series, but the emission factors (i.e., emissions per unit of activity data) derive primarily from country-reported information.

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

Mitigation Estimates: Methods

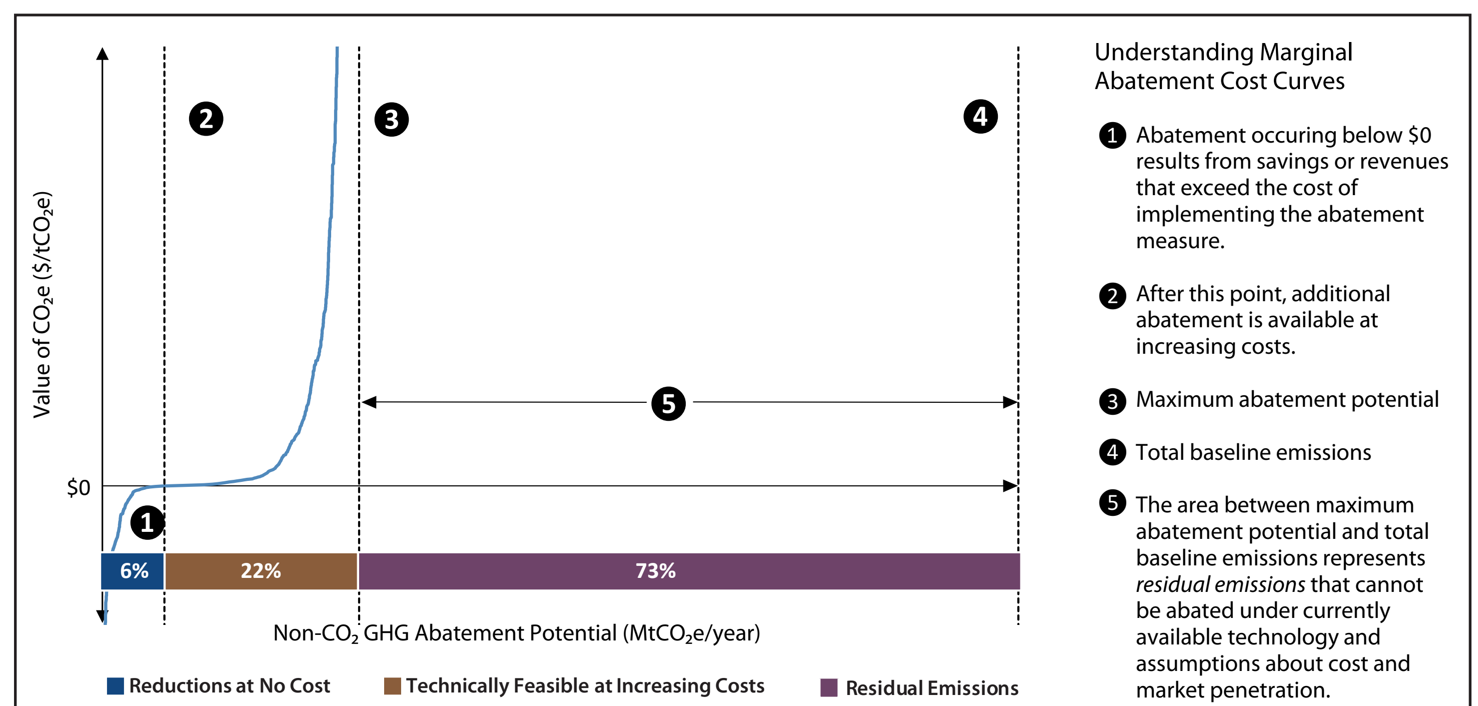
The mitigation option analysis throughout this report was conducted using a common methodology and framework. MAC curves were constructed for each region and sector by estimating the "break-even" price at which the present-value benefits and costs for each mitigation option equilibrate. The methodology produces a curve where each point reflects the average price and reduction potential if a mitigation technology were applied across the sector. In conjunction with appropriate baseline and projected emissions for a given sector, the results are expressed in terms of absolute reductions of CO_2 equivalents (million metric tons of CO_2 equivalents, $MtCO_2e$). For example, at a price of zero dollars per metric ton of CO_2 equivalent (tCO_2e), The figure below shows the level of global abatement available in 2030 at the point where the curve crosses the horizontal x-axis (785 $MtCO_2e$). These reductions are available given current technologies at no cost and represent 6% of total emissions. Another 22% of BAU emissions can be mitigated at increasing prices, up to a total of 3,805 $MtCO_2e$, the maximum abatement potential. This leaves 73% of total emissions as a residual.

The mitigation analysis accounts for country differences in industry structure and available infrastructure when data

Business-as-Usual Projections

In this report, the terms "business as usual," "BAU," and "baseline" all refer to the non-CO_2 emission projection results and are used interchangeably. The BAU scenario uses projected emission rates consistent with historical levels and does not model future effects of policy changes.

Illustrative MAC Curve



are available on a sector-by-sector basis. Additionally, the analysis accounts for country/regional differences in the price of mitigation through a series of international cost indices (labor, nonenergy materials, energy) to create a more heterogenous representation of emissions and mitigation costs and benefits across countries.

The MAC curves that describe the mitigation estimates in this report represent the techno-economic mitigation potential for each source and technology evaluated.

Derived from a bottom-up engineering cost analysis, the MAC curves represent emission reductions available at incrementally higher prices. The total technical potential refers to the maximum technically achievable emission reduction from a given source or mitigation option. The mitigation at a given price represents the emission reductions that are economic, or the break-even point, at that price incentive (e.g., \$0 per ton of CO_2 equivalent [tCO_2e]).

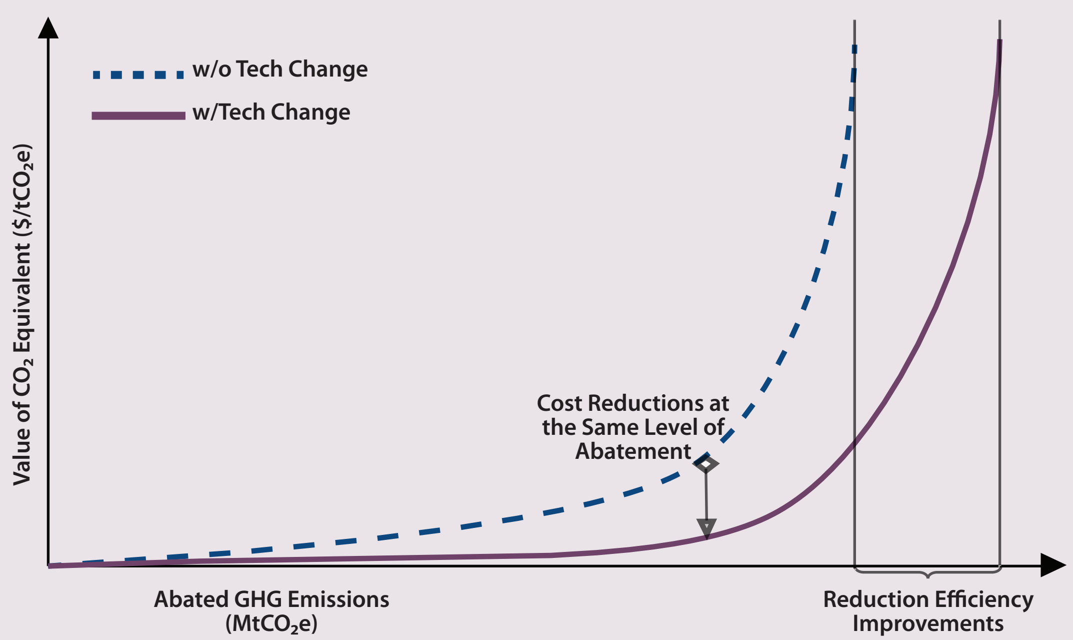
Methodological Enhancements

For this report, updates to the MAC model introduced two major methodological enhancements: incorporating the effects of technology change on mitigation costs and their reduction efficiencies and developing regionalized sectoral MAC curves for the United States. This report has a global focus and reports non-CO_2 GHG emission projections and mitigation estimates at the country level.

The incorporation of technology change in existing MAC curve calculations implies two important updates to the previous estimates. First, static capital, labor energy, and materials factors are now allowed to adjust every year, representing cost savings due to technological change.

Second, by applying a reduction efficiency improvement factor to the current technical effectiveness for each mitigation option in the model, a dynamic reduction efficiency factor was introduced that improves over time. The figure below depicts the effects of implementing technological change in the MAC model. The result is a shift of the vertical asymptote (maximum abatement potential line in the figure) outward due to the reduction efficiency improvements, thereby increasing the total technical mitigation potential. The cost reductions associated with the learning curve result in a downward shift of parts of the MAC curve, effectively lowering abatement costs.

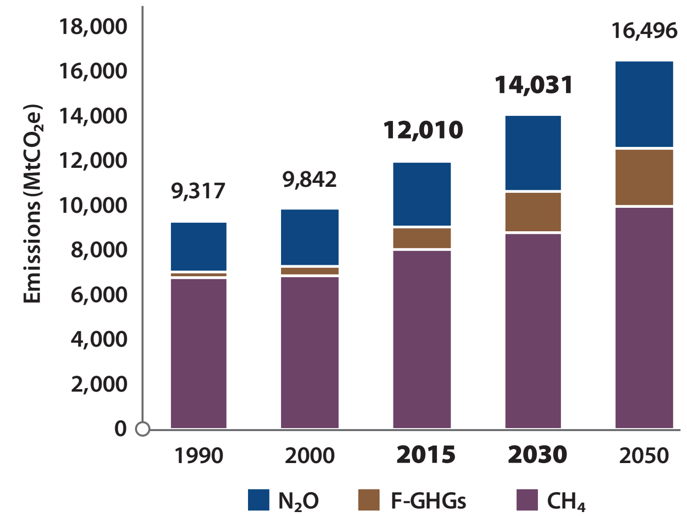
Illustrative MAC Curve Showing the Effects of Technological Change



Global Results

Between 1990 and 2015, global non-CO_2 emission levels rose by about 29%. Over this same period emissions of CH_4 increased 19%, N_2O emissions increased 32%, and F-GHG emissions increased 231%. Between 2015 and 2030, global non-CO_2 emissions are estimated to continue to increase by approximately 17%, growing from 12,010 to 14,031 $MtCO_2e$. Emissions of F-GHGs are projected to increase 86% from 2015 through 2030, much faster than CH_4 (9%) and N_2O (14%).

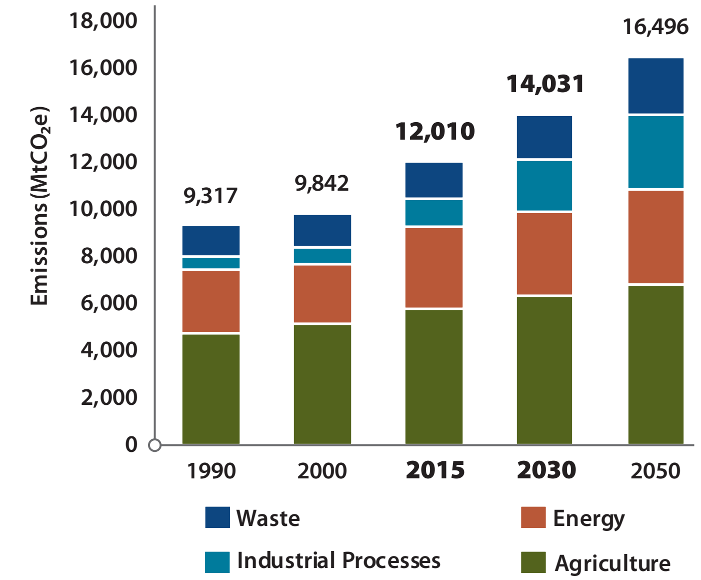
Global Non-CO_2 Emissions by Gas ($MtCO_2e$)



This projection represents a BAU scenario using emission rates consistent with historical levels and that does not model future changes resulting from policies and measures.

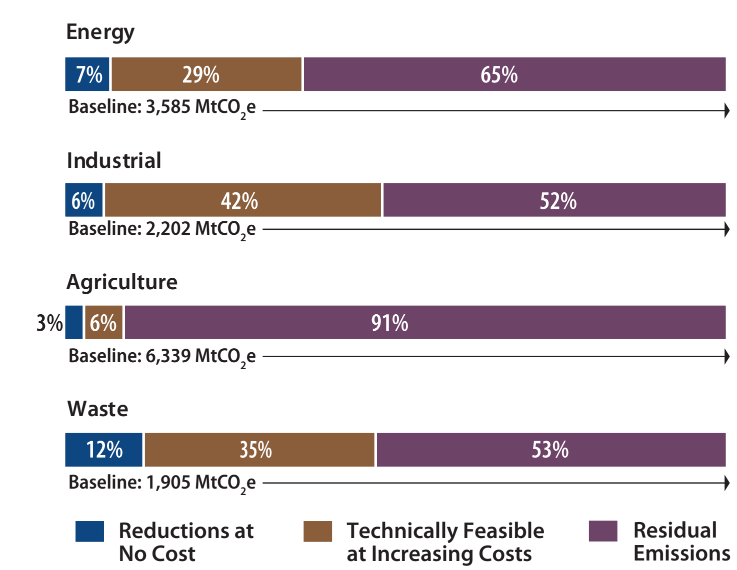
In 2030, the total global non-CO_2 GHG mitigation potential is estimated to be approximately 3,805 $MtCO_2e$, or 27% of non-CO_2 GHG emissions in that year. The total estimated mitigation potential from CH_4 is approximately 2,600 $MtCO_2e$, representing 68% of total non-CO_2 GHG mitigation potential in 2030. Mitigation potential from F-GHGs is estimated to be about 829 $MtCO_2e$ in 2030, or 22% of total non-CO_2 GHG mitigation potential in 2030. F-GHG mitigation potential is estimated to more than double to 2,086 $MtCO_2e$ in 2050 as baseline emissions from F-GHG sources are projected to grow over time.

Global Non-CO_2 Emissions, by Sector ($MtCO_2e$)



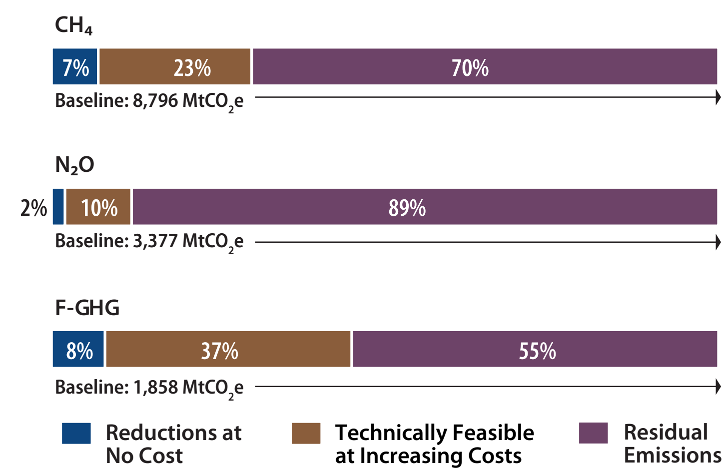
In 2030, the energy sector accounts for 1,265 $MtCO_2e$ of mitigation potential followed closely by the waste sector at 887 $MtCO_2e$. The industrial processes and agriculture sectors account for 1,060 and 681 $MtCO_2e$ of mitigation potential, respectively. The total technical mitigation potential from the agriculture sector accounts for 10% of baseline emissions in 2030, while the mitigation potential from the energy and waste sectors accounts for 35% and 47% of baseline emissions, respectively.

Mitigation Potential and Residual Emissions by Sector, 2030



The mitigation potential for CH_4 is 30% of baseline emissions, while the mitigation potentials for N_2O and F-GHGs are 12% and 45%, respectively.

Mitigation Potential and Residual Emissions by Gas, 2030

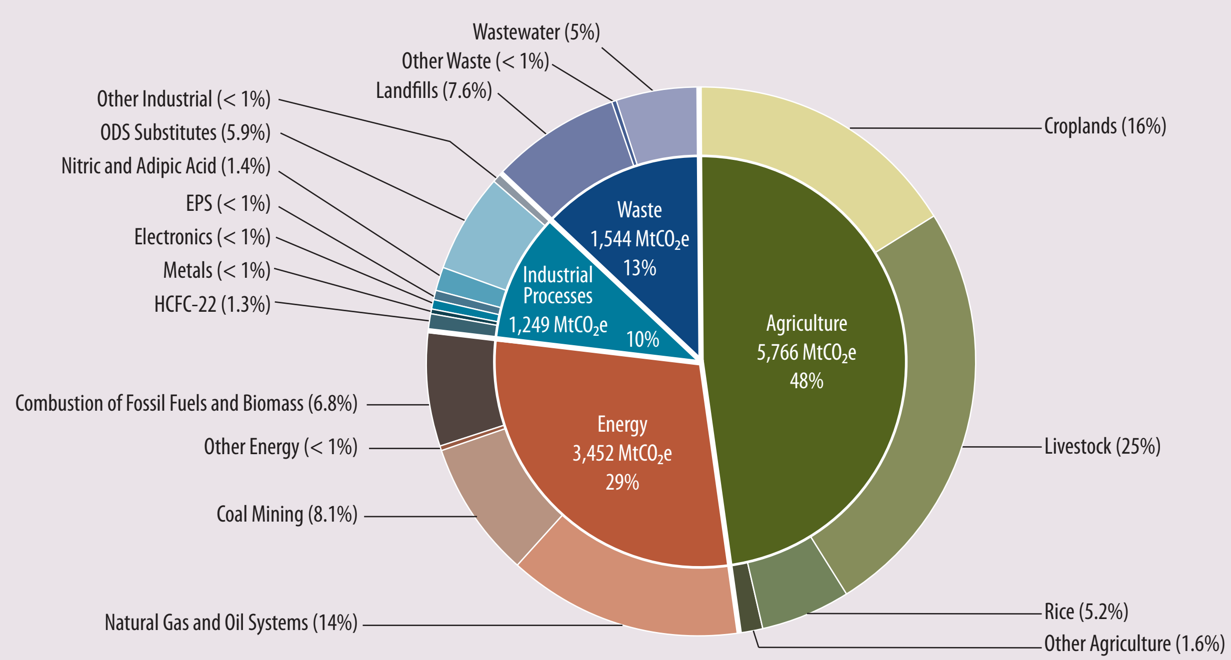


The following figure shows the total BAU emission projections (dashed line), emissions resulting from implementing cost-effective mitigation potential at marginal costs (abbreviated as MC in the figure legend) less than $0/t$CO_2$e (solid line), and residual emissions by sector after all technically available mitigation technologies have been applied. In 2030, the total mitigation potential is 3,805 MtCO_2e, a 27% reduction in total global non-CO_2 emissions below the baseline projection. The figure shows that over time non-CO_2 emissions can be held roughly constant by deploying available mitigation technologies. These emissions that remain after mitigation options are implemented are called "residual" emissions. Achieving long-term reductions of non-CO_2 emissions below the 2015 level would require development of new or more effective mitigation technologies.

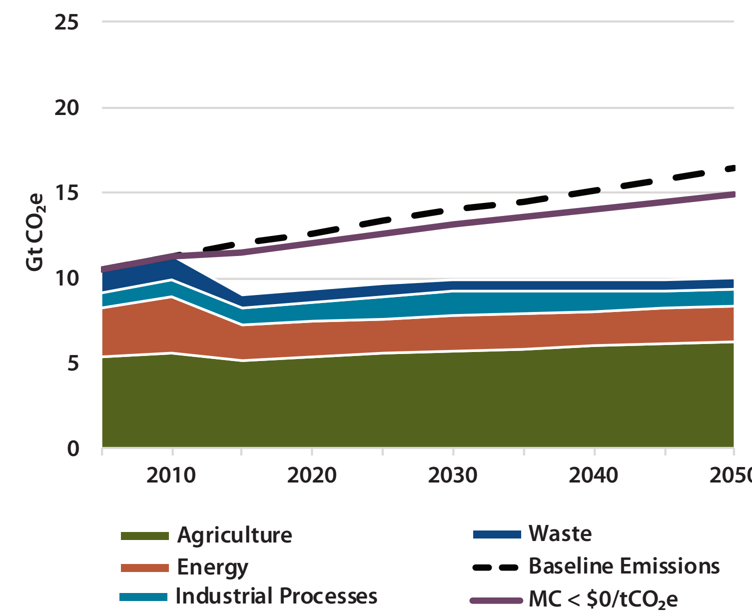
Global Non-CO_2 Emissions

For this report, emission sources were grouped into four economic sectors: energy, industrial processes, agriculture, and waste. Although CO_2 emissions are concentrated in the energy sector, agriculture accounts for the largest share of non-CO_2 emissions throughout the time series. Emissions from the industrial processes and waste sectors are projected to grow at the fastest rates between 2015 and 2030, 76% and 23%, respectively.

Global Non-CO_2 Emissions by Sector and Source, 2015



BAU Emission Projections and Residual Emissions by Sector



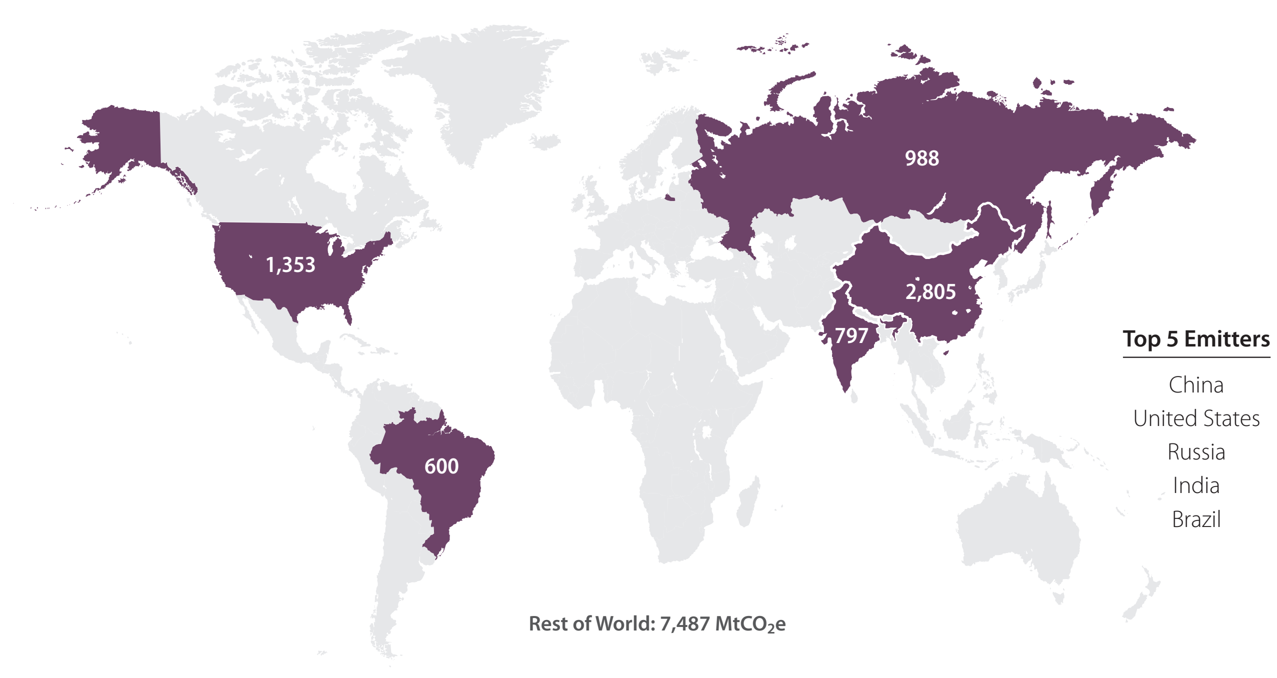
MC = marginal cost.

Country-Level Results

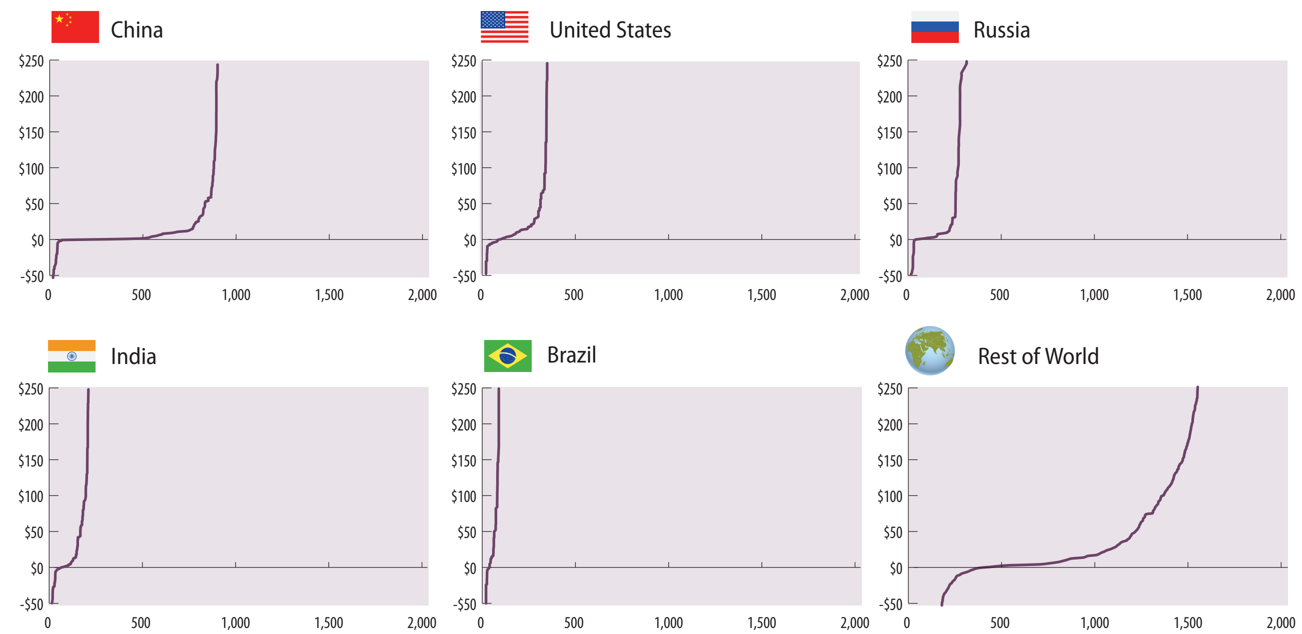
In addition to global results, throughout this report each source category discussion includes information on top countries' baseline projections and mitigation potential. Globally, the countries with the top 5 total non-CO_2 GHG emissions in 2030 under the BAU scenario are China, the United States, Russia, India, and Brazil. The maps are annotated with 2030 emissions in MtCO_2e. Because these countries have some of the largest economies globally, they are among the top emitters in many source categories as well.

In many cases, the countries with the largest baseline emissions are also the countries with the largest mitigation potential. The following panel displays MAC curves for the top 5 countries with the largest non-CO_2 GHG BAU emissions in 2030 along with a MAC curve representing the mitigation potential from the rest of the world.

Countries with the Largest Emissions, 2030



Marginal Abatement Cost Curves, 2030



Uses and Application of Non-CO_2 GHG Emission Projections and Mitigation Estimates Data

The emission projections and mitigation datasets in this report are intended to provide technical information that can be useful in economic modeling and climate mitigation analysis. The results have not been evaluated with respect to their fitness for particular applications. These non-CO_2 datasets are of particular use to economic and integrated assessment models that evaluate the effect of GHG emissions and the cost and availability of mitigation from the non-CO_2 GHG sectors. A consistent framework across countries and regions, such as the one applied to develop these data, is particularly useful for models that have a global or large regional spatial coverage.

The results in this report are generally presented at aggregate source and sector levels with country- and subsource-level detail. The underlying non-CO_2 emission and mitigation data are available at the source and country levels. Because of the global coverage of this analysis, there is limited ability to capture the unique circumstances of countries. In some cases, specific country-level historical emission inventories were unavailable. In these instances, the EPA used calculated estimates based on default methodologies and emission factors. In other cases, countries reported non-CO_2 GHG emissions in their inventories for source categories not included in the projections or mitigation analyses. For completeness, these are included in sector charts and underlying datasets as "Other Energy," "Other Agriculture," etc., but no analysis was done on these emissions. Subsource disaggregation is based on default methodologies and may not match country-reported information. Depending on activity data projections available for each source category, projected trends may reflect large regions or in some cases global aggregate demand trends. For the mitigation estimates, although the EPA strove to capture regional heterogeneity, data to model mitigation technology implementation at the country level are limited. In these cases, data were extrapolated from known conditions in other proximate or similar regions.

Details about each source and mitigation option modeled, as well as specific information about the estimation of emission projections, are available in the accompanying methodology document to this report, *Global Non-CO_2 Greenhouse Gas Emission Projections & Marginal Abatement Cost Analysis: Methodology Documentation.*

ENERGY

Introduction

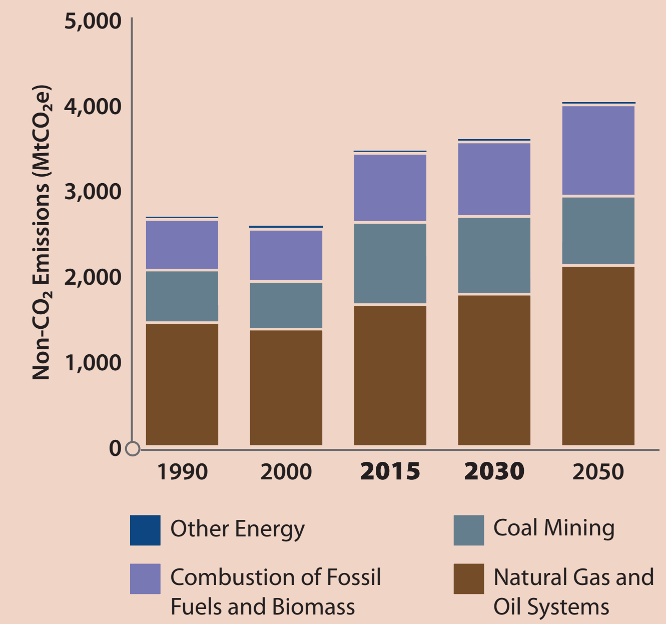
The energy sector is the second largest contributing sector to global emissions of non-CO_2 GHGs, accounting for 29% of global non-CO_2 emissions in 2015. This section presents global energy-sector CH_4 and N_2O historical and projected emissions and the mitigation potential for the following source categories:

- Coal mining (CH_4)
- Natural gas and oil systems (CH_4)
- Combustion of fossil fuels and biomass (CH_4, N_2O)

Projections were estimated for all sources; however, complete data to estimate MAC curves globally are available for only coal mining and natural gas and oil systems. These two sources represented 28% and 48% of energy-related emissions in 2015, respectively. Energy-sector emissions increased 29% between 1990 and 2015.

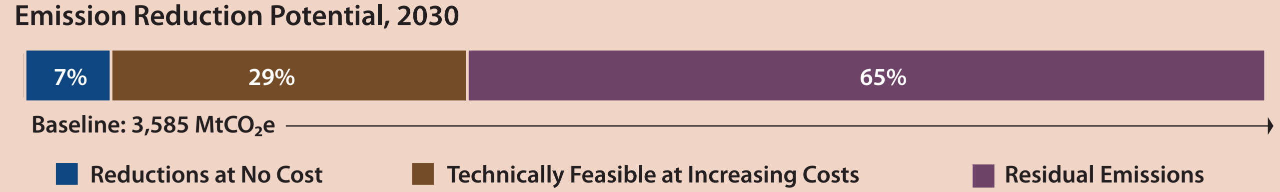
Between 2015 and 2030, global energy-sector emissions are projected to increase 4% under a BAU scenario, reaching 3,585 $MtCO_2e$ in 2030. Natural gas and oil activities are projected to remain the largest contributor to non-CO_2 emissions from the energy sector; stationary and mobile combustion emissions are projected to grow 15% between 2015 and 2030, thereby surpassing coal mining emissions as the second largest contributor for this sector. Emissions from coal mining activities are projected to decrease by 6% between 2015 and 2030 as the energy sector transitions from coal to natural gas.

Historical and Projected Emissions from the Energy Sector



Mitigation potential from the energy sector is approximately 1,265 $MtCO_2e$ in 2030, accounting for 64% of coal emissions and 38% of oil and gas emissions. Mitigation potential in the energy sector represents 33% of total global non-CO_2 mitigation potential in 2030.

Emission Reduction Potential, 2030



Coal Mining

Source Background

CH_4 is produced during the process of coalification, where vegetation is converted by geological and biological forces into coal. Coal seams and the surrounding rock strata store CH_4. Natural erosion, faulting, or mining can reduce pressure above or surrounding the coal bed and liberate the CH_4. Because CH_4 is explosive, the gas must be removed from underground mines high in CH_4 as a safety precaution.

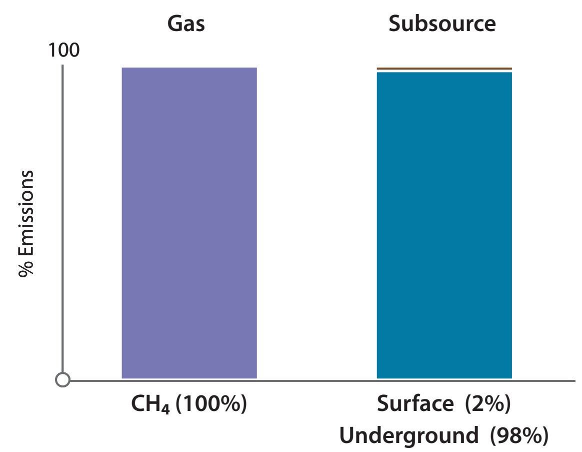
The quantity of gas emitted from mining operations is a function of two primary factors: coal rank and coal depth. Coal rank is a measure of the carbon content of the coal, with higher ranks corresponding to higher carbon and CH_4 content. Coals such as anthracite and semianthracite have the highest coal ranks, while peat and lignite have the lowest. Pressure increases with depth and prevents CH_4 from migrating to the surface; thus, underground mining operations typically emit more CH_4 than surface mining operations. Additionally, post-mining processing of coal and abandoned mines release CH_4.

Historical Trends

Between 1990 and 2015, global CH_4 emissions from coal mining are estimated to have increased by 54%. Underlying this trend have been increases in global coal production with volumes increasing by 60% over the period. Emissions have increased in step with production, suggesting low historical mitigation of CH_4 from coal mining.

2030 Emissions by Gas and Subsource

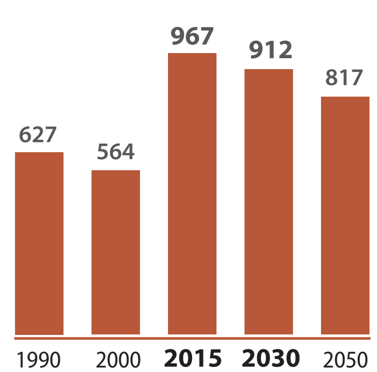
Underground mining constitutes almost the entirety of all emissions at approximately 98%, while surface mining has little impact on the results.[14]



Projected Emissions & Top Emitting Countries

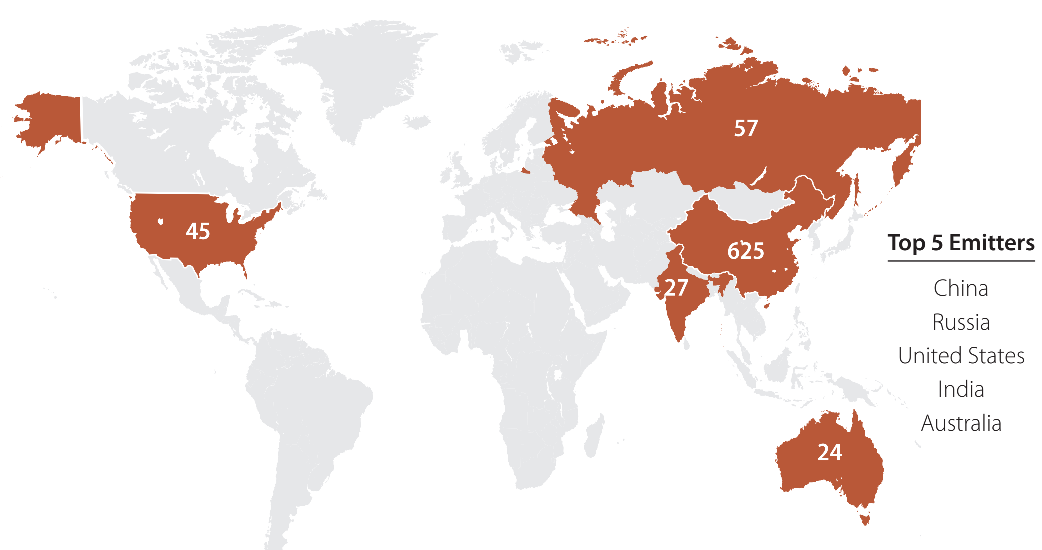
Emissions ($MtCO_2e$)

From 2015 through 2030, emissions are projected to decrease by about 6% to approximately 912 $MtCO_2e$ in 2030.



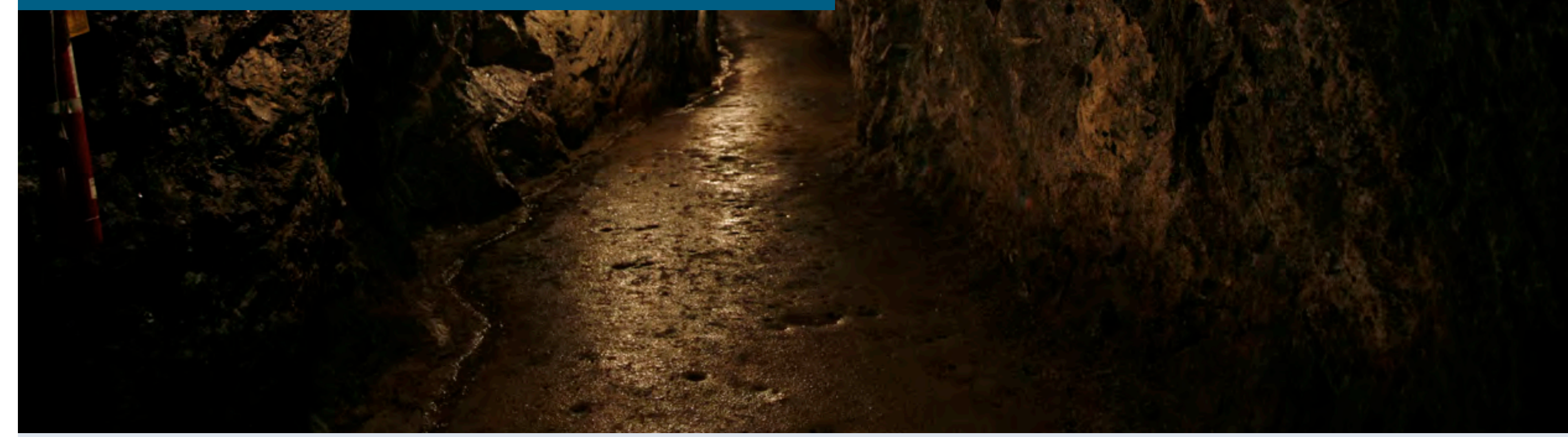
2030 Emissions from Top 5 Emitting Countries

Rest of World: 133 $MtCO_2e$



Key Points

- Coal mining accounts for 6% of total global anthropogenic non-CO_2 GHG emissions in 2030.
- Expected reductions in reliance on coal in certain major consuming countries such as China, the United States, and Russia cause global emissions to decrease in future years, which offsets expected increases in other countries such as India.
- Underground mining is the largest contributor of emissions from coal mining because of a higher proportion of total production from this activity and higher emissions intensity than surface mining.



Projected Trends

From 2015 through 2030, CH_4 emissions from coal mining are projected to decrease by about 6%. This projection corresponds to expected decreases in reliance from major coal-consuming countries such as the United States and China, while global growth remains fairly flat.[15]

The 10 top emitting countries comprise 94% of global emissions in 2030. Each of these top emitters ranks within the top 10 in total coal production in 2015. By 2030, China is the largest contributor to emissions from coal mining based on extensive production and use of this resource. However, China's reliance on coal is expected to decline because of a slowing economy, reduction commitments, and policies currently being implemented to address air pollution. The U.S. Energy Information Administration (EIA) projects coal consumption in China to decrease by 6% from 2015 through 2030; however, the country remains the largest emitter throughout the same projection period.[16] In contrast, India is the fourth highest emitter in 2030 based on projected increases in the country's reliance on coal in future years.

Underground Mining

Underground mining represents the majority of coal produced globally. Projections are driven by regional or country-specific consumption, which decreases in a number of major consuming countries.[17] Generated emission volumes are significantly larger from this activity than surface mining per unit of production. Given this and the higher proportion of total production from this activity, this subsource is the main contributor to coal mining source category emission results.

Surface Mining

European countries tend to have higher proportions of surface mining compared to underground, although those countries represent a small portion of global production. Projections are driven by consumption, which is expected to remain fairly flat globally but to decrease in certain countries.[18] Emissions generated from this practice are less intensive compared to underground mining. Given lower production and less intensity per unit of production, this subsource does not have as much of an impact on overall results.

Key Points

- **The global CH_4 abatement potential in coal mining is projected to be 582 $MtCO_2e$ (64% of baseline emissions) in 2030.**
- **An estimated 2% of abatement potential in the coal source category can be achieved at prices below $0/$tCO_2e$; 95% of abatement potential is technically feasible at prices below $20/$tCO_2e$.**
- **This analysis did not model abatement measures for surface mining.**

Abatement Measures

This analysis considered six abatement measures for CH_4 emissions in underground coal mining: recovery for pipeline injection, power generation, process heating, flaring, and catalytic or thermal oxidation of ventilation air methane (VAM). These reduction technologies consist of one or more of the following primary components: (1) a drainage and recovery system to remove CH_4 from the underground coal seam, (2) the end-use application for the gas recovered from the drainage system, and (3) the VAM recovery or mitigation system.

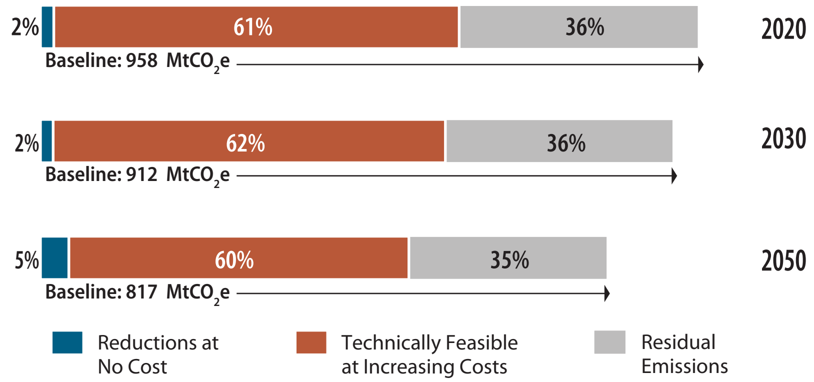
High-quality CH_4 is recoverable from coal seams by drilling vertical wells from the surface up to 10 years in advance of a mining operation or drilling in-mine horizontal boreholes several months or years before mining. However, most mine operators exercise just-in-time management in developing new operations; subsequently, horizontal cross-panel boreholes are installed and drain gas for 6 months or less.

Once recovered, CH_4 can be used for energy purposes. Specifically, recovered CH_4 can be injected into a natural gas pipeline or used on-site for electricity or heat generation. Recovered CH_4 that is not used for energy can be flared instead of released into the atmosphere. Flaring results in a lower GWP than allowing the CH_4 to directly enter the atmosphere. At mines where the ventilated mine air has a low concentration of CH_4 (0.25% to 1.25%), the recovered gas can be oxidized and combusted. The by-products of the combustion process are water and CO_2.

Coal Mining

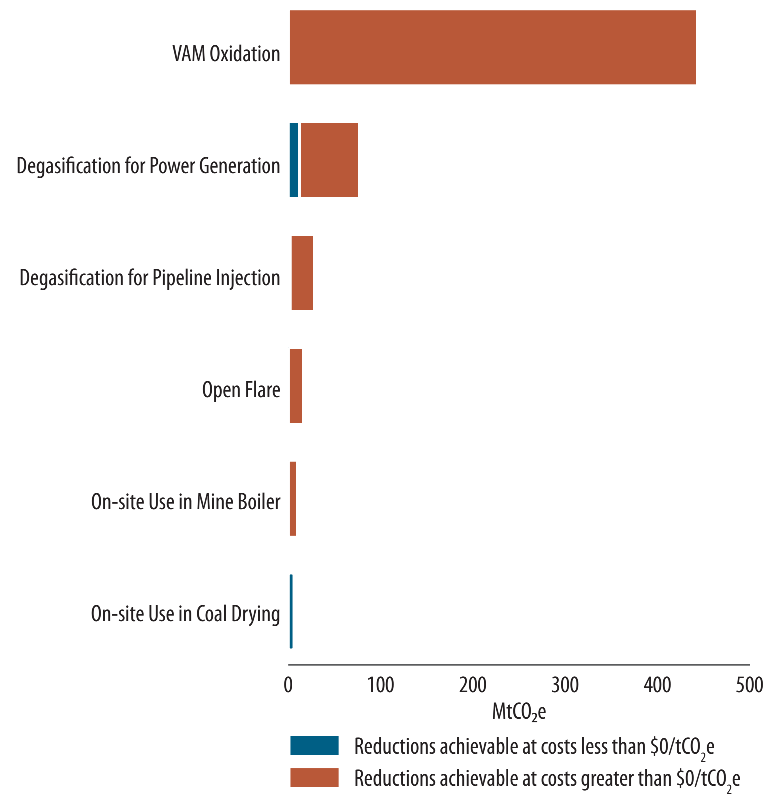
Total Reduction Potential

Reducing emissions by 2% compared with the 2020 baseline is cost-effective (below $0/$tCO_2e$). An additional 61% reduction is available using technologies with increasingly higher costs. The cost-effective reduction potential remains at 2% in 2030 but rises to 5% in 2050.



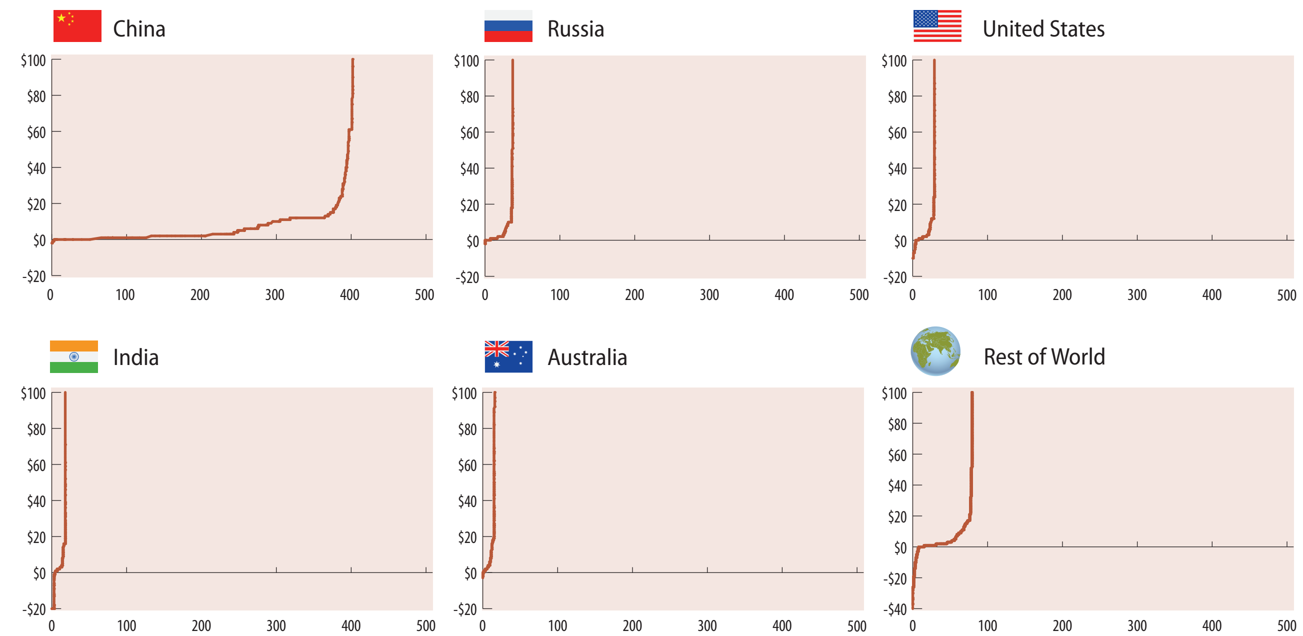
Reduction Potential by Technology

In 2030, VAM oxidation is the leading emission abatement measure, but using degasification for power generation presents the largest abatement potential at prices below $0/$tCO_2e$. The two technologies combined contribute 90% of potential abatement in 2030.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of emissions represent 86% of all potential global abatement from coal mining in 2030. China is responsible for 69% of global abatement potential in coal mining (403 $MtCO_2e$).



Abatement Potential

In 2030, the adoption of the suite of abatement measures considered in this analysis can reduce total annual emissions from coal mining by approximately 64%. The MAC curve analysis results show that 78% of potential CH_4 abatement is achievable at prices below $10/$tCO_2e$. At or below a break-even price of $20 or less, 95% of abatement potential is technically feasible.

In 2030, the top 3 mitigation technologies globally are the use of stand-alone VAM, degasification for power generation, and degasification for pipeline injection. Using stand-alone VAM can abate up to 443 $MtCO_2e$ (76% of coal mining's total abatement potential), although it is one of the most expensive abatement options in coal mining because of three key factors: (1) the equipment itself is large and costly; (2) there is no revenue source; and (3) only a handful of technologies have been demonstrated at a commercial scale and, as such, economies of scale in production have not been realized. Technology improvements have the potential to reduce the costs of VAM oxidation technology, making more of the potential abatement economically feasible for mine operators.

Degasification technologies and on-site gas use for coal drying can provide abatement at below costs of $0/$tCO_2e$, representing savings or a potential revenue stream, but only 20 $MtCO_2e$ of cost-effective abatement is available, which represents only 3% of baseline emissions. For costs greater than $0/$tCO_2e$, degasification technologies contribute 16% of the total annual abatement potential.

In 2030, China, Russia, and the United States have the highest abatement potential for coal. China alone represents 69% of the global mitigation potential in coal mining, while Russia and the United States represent 6% and 5%, respectively.

Natural Gas and Oil Systems

Production, Transmission, Distribution, Refining

Source Background

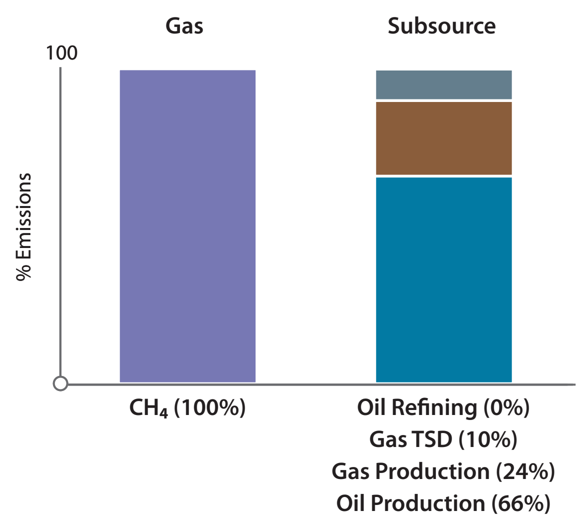
CH_4 is the principal component of natural gas and is emitted during natural gas production, processing, transmission, and distribution. Oil production and processing upstream of oil refineries can also emit CH_4 in significant quantities as natural gas is often found in conjunction with petroleum deposits. In both systems, CH_4 is a fugitive emission from leaking equipment, system upsets, 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.

Historical Trends

Between 1990 and 2015, global CH_4 emissions from natural gas and oil systems increased by an estimated 15%. African and Middle Eastern countries have been major contributors to this increase as both regions have nearly doubled emissions during this time. Over this same period, world natural gas production increased about 70% and oil production increased 33%. In recent decades, there have been numerous oil and gas initiatives aimed at reducing emissions. The fact that production has grown faster than emissions indicates that average rates of CH_4 emissions per unit of oil and gas production have decreased as a result of past efforts to reduce CH_4 emissions from this source.

2030 Emissions by Gas and Subsource

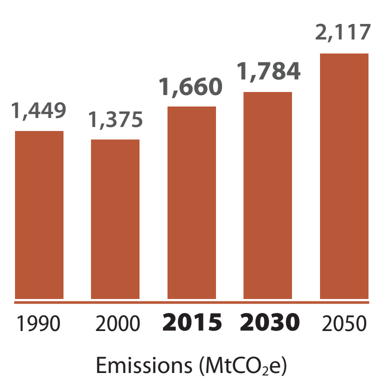
Oil production constitutes the bulk of emissions at approximately 66%.[19]



Projected Emissions & Top Emitting Countries

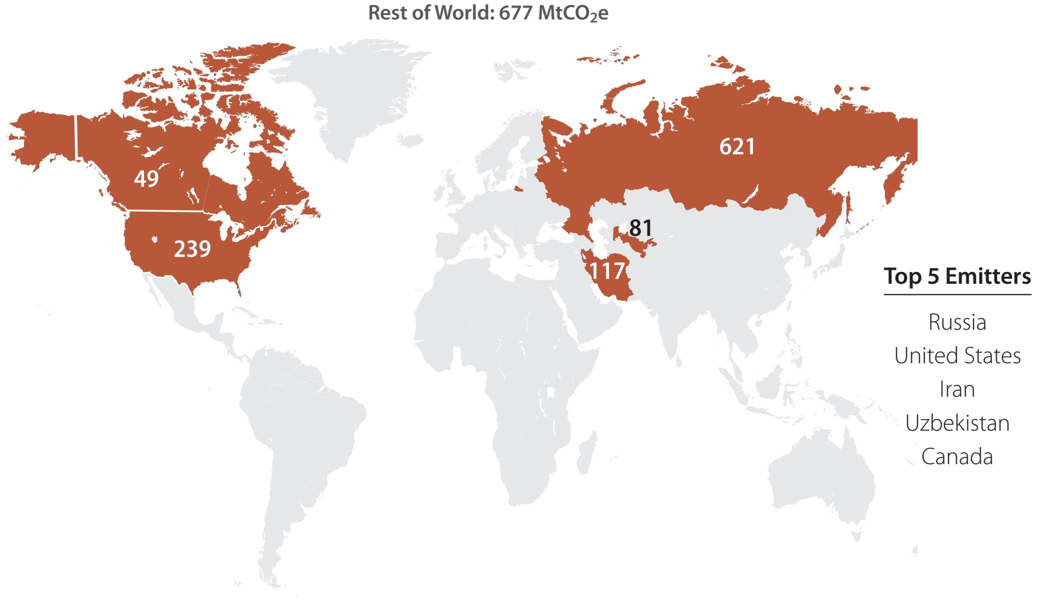
Emissions ($MtCO_2e$)

From 2015 through 2030, emissions are projected to increase by about 8% to approximately 1,784 $MtCO_2e$ in 2030.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 677 $MtCO_2e$



Key Points

- **Natural gas and oil systems account for 14% of total global anthropogenic non-CO_2 GHG emissions in 2030.**
- **Increasing emissions correspond to projected increases in natural gas and oil production volumes.**
- **Generally, the International Energy Outlook projects increasing production, which constitutes the bulk of emissions from all operations. As such, top emitting country estimates increase steadily through 2030.[20]**

Projected Trends

From 2015 through 2030, CH_4 emissions from natural gas and oil systems are projected to increase by about 8% under the BAU scenario.[21,22] This projection corresponds to increases in natural gas (+7%) and oil production (+19%) based on EIA's International Energy Outlook Reference Case scenario.[23]

In 2030, the top 10 emitting countries comprise approximately 73% of global emissions. Four of these top emitters rank within the top 10 in total oil and gas production in both 2015 and 2030, which contributes to higher emissions. By 2030, Russia contributes the most emissions globally from natural gas and oil systems. With known large reserves of oil and gas and a general lower quality of infrastructure, Russia's emissions are expected to increase. In the United States, advances in production technology have allowed exploitation of vast shale gas reserves, increasing production volumes substantially. Oil production is expected to increase in the United States 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.

Current emission calculations are based on the 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.

Disaggregated results are discussed in the following section. The disaggregated results here are based on default emission calculations. Subsource emissions were disaggregated by using the proportion of each segment's emissions determined using default calculations for that country based on production and consumption volumes and IPCC Tier 1 emission factors.[24] Although in some cases country-reported disaggregated results may be available, country-reported data at the subsource level were not incorporated in this analysis.

Natural Gas and Oil Systems

Production, Transmission, Distribution, Refining

Gas Production and Processing

Gas production and processing is associated with the withdrawal and subsequent processing of underground raw natural gas. Emission estimates are based on the amount of natural gas produced within each country and an aggregated IPCC emission factor. These results have a relatively large impact on overall results. Generally, gas production is projected to increase globally. Particularly in countries such as Australia, China, and Brazil, natural gas production is expected to increase by over 40% between 2015 and 2030 according to EIA. These increases are expected to result in higher global emissions, despite declining production across European countries.

Gas Transmission, Storage, and Distribution

Emissions for gas transmission, storage, and distribution are associated with the downstream transportation of pipeline-quality gas from the processing facility to either storage or for customer usage. Emission estimates are based on the quantity of gas consumed within each country and an aggregated IPCC factor. Downstream emissions represented in this disaggregation do not have as large an impact on overall results as gas or oil production. Globally, gas consumption is expected to increase. Specifically, China is expected to be a major natural gas consumer in future years. Despite increasing production rates within the country, demand is expected to outpace production. Other major natural gas–producing countries such as Qatar, Australia, and the United States are already competing to align themselves with the ability to provide long-term supplies of natural gas to China to meet record expected demand. Other countries in Asia and the Middle East are also expected to increase gas consumption from 2015 through 2030, thereby increasing overall emissions.

Oil Production

Oil production is the largest contributing segment to emissions from natural gas and oil systems and has the most noticeable impact on overall results. Emissions from oil wells originate from on-site operations either associated with the direct withdrawal of oil or from the on-site processing equipment used. Emission estimates are based on the quantity of oil produced within each country and an aggregated IPCC factor. This segment is the most influential due to high IPCC emission factors for oil production. Similar to natural gas production, oil production is expected to increase globally from 2015 through 2030. Middle Eastern and African countries are projected to increase oil production from 2015 through 2030. With the emergence of hydraulic fracturing technologies, the United States is currently producing oil at record high volumes. Projections expect production increases to continue. Thus, global emissions are also expected to rise over time.

Oil Refining

Emissions in this segment are caused by equipment fugitive leaks and vented emissions from certain maintenance processes associated with the processing and refining of raw crude within oil refineries such as blowdowns. Because most of the contained CH_4 is removed from crude oil by the time of delivery to the refinery, CH_4 emissions from this segment are generally minor. Given this (as is also represented by the low aggregated IPCC factor), emissions from this segment have minimal impact on overall results. Emissions from oil refining are driven by oil consumption, which is expected to gradually increase from 2015 through 2030 globally.

IPCC Emission Factor Sensitivity Analysis

The EPA reviewed three additional cases of results to examine the impact of three ranges provided for certain IPCC emission factors. The three ranges—high, low, and geometric average—were applied to the aggregate IPCC emission factors used to calculate Tier 1 estimates to investigate the impact of the different factors on overall emission estimates. A particular IPCC factor did not vary between cases if a range was not provided. As expected, Tier 1 emission results are higher using the upper range and lower using the lower range. The low case Tier 1 emission results are closest to the EPA's composite emission results, as country-reported estimates are generally lower than that determined using IPCC factors. The geometric average case also did not vary much with the primary results based on an aggregate factor using the direct average of the range.

The following table lists overall emission results varying for each of the cases. This overall result is a combination of Tier 1 calculations and UNFCCC country-reported emission estimates and can vary based on several factors such as trends in country-specific production or consumption. The low case varied the most from the aggregate case, mainly due to a substantial drop in the gas production subsource.

Comparison of Emission Factor Approaches

Emission Factor Approach	2030 Global Emission Estimate ($MtCO_2e$)
Aggregate *(chosen emission factor for projections)*[a]	1,784
Case 1: High	1,878 (+5.3%, average)
Case 2: Low	1,656 (-7.2%, average)
Case 3: Geometric Average	1,706 (-4.3%, average)

[a] Aggregate emission factors represent the average of the IPCC emission factor ranges used to generate results.

While having an impact on overall emission results, the revised IPCC ranges also vary the disaggregation of emissions based on Tier 1 estimates. As oil production and gas production are the most influential segments on emissions, varying the ranges of these aggregate IPCC factors noticeably impacts segment emissions. The gas production segment experiences the most discernable impact from the change in ranges, as the low case is substantially lower than the aggregate case.

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 emission of GHGs, new legislation and voluntary carbon markets are developing to increase energy production efficiency in the natural gas and oil industry.

"Projected increases in natural gas and oil production and consumption volumes across many countries are expected to contribute to higher future emissions."

Natural Gas and Oil Systems

Production, Transmission, Distribution, Refining

Key Points

- **The global abatement potential from natural gas and oil systems is 684 $MtCO_2e$, roughly 38% of baseline emissions in 2030.**
- **The abatement potential at cost-effective prices ($0/$tCO_2e$) is estimated to be 12% of the natural gas and oil baseline in 2030, rising to 23% at prices below $20/$tCO_2e$.**
- **Available abatement measures in the natural gas and oil production segment account for up to 38% of total abatement potential from natural gas and oil systems.**

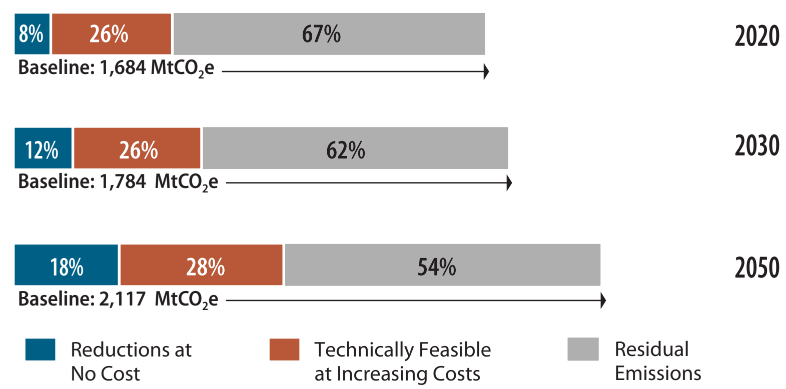
Abatement Measures

In total, this analysis evaluated 28 abatement measures for their potential to mitigate CH_4 emissions associated with the four natural gas and oil system segments—production, processing, transmission, and distribution. Abatement measures documented by the EPA's Natural Gas STAR Program served as the basis for estimating the costs of abatement measures used in this analysis.[25] Measures typically fall into three categories: equipment modifications or upgrades; changes in operational practices, including directed inspection and maintenance (DI&M); and installation of new equipment. Abatement measures are available to mitigate emissions associated with a variety of system components, including compressors, engines, dehydrators, pneumatic controls, pipelines, storage tanks, wells, and others.

DI&M programs present mitigation opportunities across all segments of natural gas and oil with no up-front capital costs and high technical effectiveness, in some cases unlocking a 95% reduction in targeted emissions. Installing plunger lift systems in gas wells has a small capital cost and technical effectiveness of only 40%, but they generate an annual revenue stream from captured gas in excess of the initial capital costs, resulting in a payback period of less than 1 year. Replacing wet seals with dry in centrifugal compressors also generates revenue but has much higher capital costs and a longer payback period. The most expensive mitigation options considered in this analysis are open flaring in offshore platforms and replacement of aging or unprotected pipeline infrastructure.

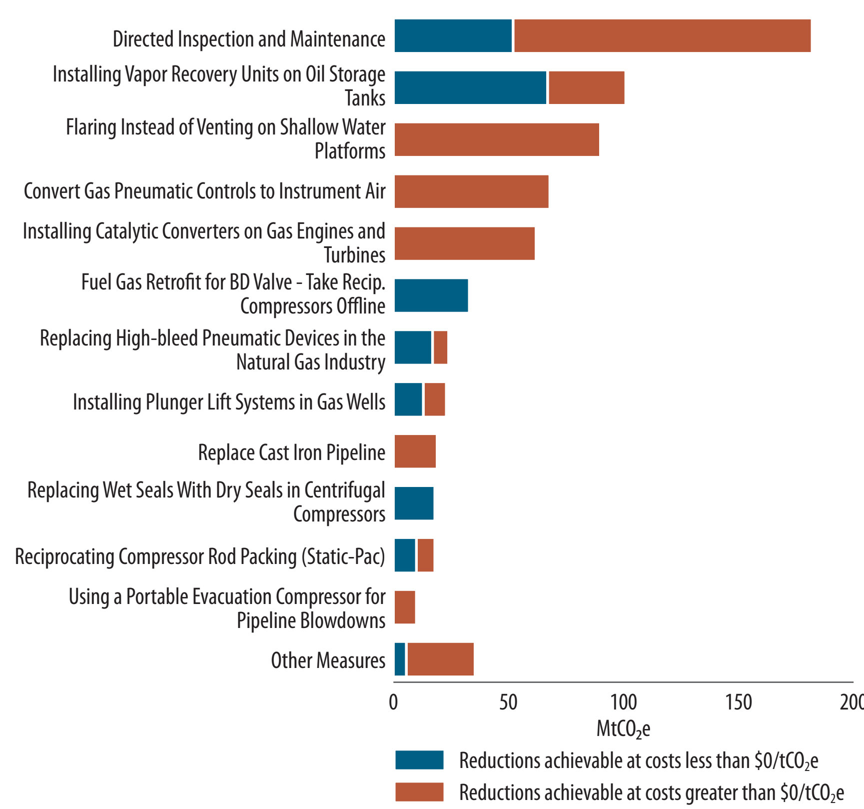
Total Reduction Potential

Reducing emissions by 8% compared with the 2020 baseline is cost-effective. An additional 26% reduction is available using technologies with increasingly higher costs. The cost-effective reduction potential rises to 12% in 2030 and 18% in 2050.



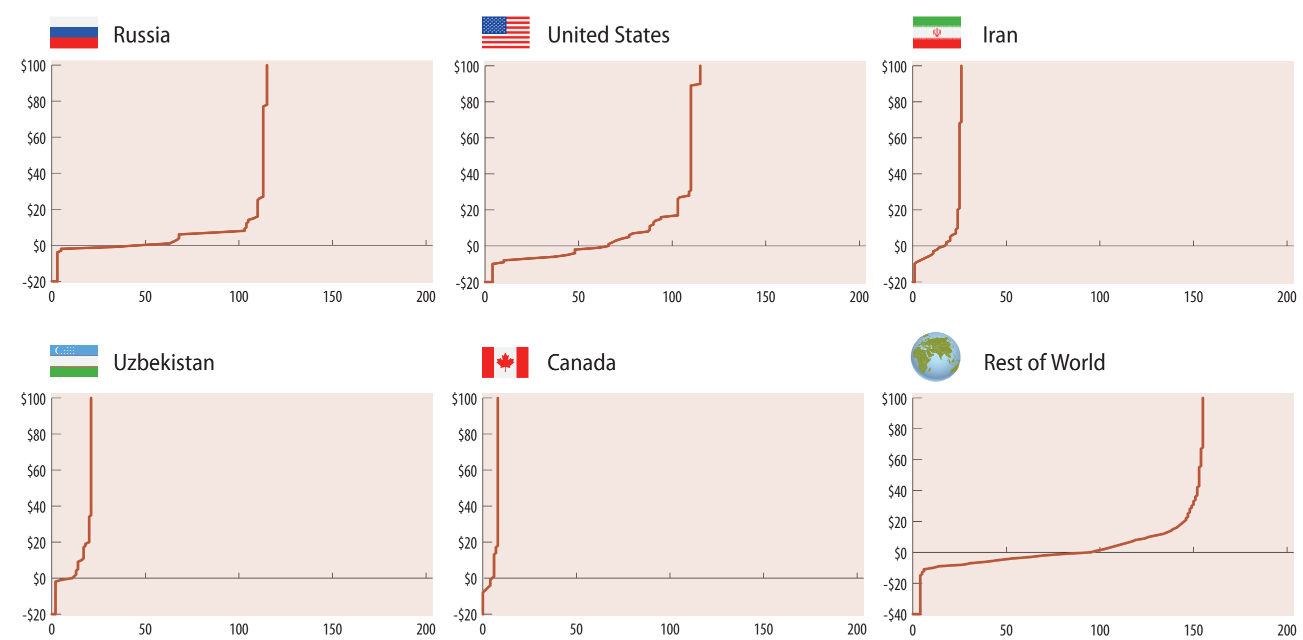
Reduction Potential by Technology

In 2030, installing vapor recovery units on oil storage tanks is the leading emission abatement measure and presents the largest abatement potential at prices below $0/$tCO_2e$. This technology contributes 9% of potential abatement in 2030.



Marginal Abatement Cost Curves, 2030

In 2030, Russia has the highest emissions from natural gas and oil systems and contributes to 32% of the global abatement potential from this source. The top 5 countries by emissions, represented by the figures below, make up 61% of total potential abatement from this source globally.



Abatement Potential

In 2015, the global abatement potential from natural gas and oil systems was 508 $MtCO_2e$, or 31% of total emissions from this source. The abatement potential is projected to increase over time to 684 $MtCO_2e$ in 2030, respectively, representing 38% of total emissions.

In 2030, abatement measures could reduce emissions by 23% at break-even prices of $20 or below. However, in 2030, 37% of potential abatement is estimated to cost more than $50/$tCO_2e$, suggesting that achieving these reductions would be difficult without reducing the cost of abatement or improving the removal efficiency of available abatement measures.

At the global scale, the two measures with the highest abatement potential, respectively, are using DI&M and installing vapor recovery units on oil storage tanks. In 2030, using DI&M potentially can reduce 52 $MtCO_2$ at below $0/$tCO_2e$ and 130 $MtCO_2$ at costs above $0/$tCO_2$. Installing vapor recovery units can achieve 67 $MtCO_2e$ at below $0/$tCO_2e$ and 34 $MtCO_2e$ at costs above $0/$tCO_2$.

At a country scale, Russia (204 $MtCO_2e$), the United States (135 $MtCO_2e$), and Iran (43 $MtCO_2e$) have the highest abatement potential in 2030. DI&M is the leading abatement option in the United States and Iran, capturing 39% and 21% of national abatement potential, respectively. At break-even prices below $0/$tCO_2e$, DI&M offers 28 $MtCO_2e$ and 2.5 $MtCO_2e$ of abatement for the United States and Iran, respectively. In Russia, installing vapor recovery units on oil storage tanks and using DI&M contribute to 24% of national abatement potential.

Combustion of Fossil Fuels and Biomass

CH_4 and N_2O Emissions from Combustion

Source Background

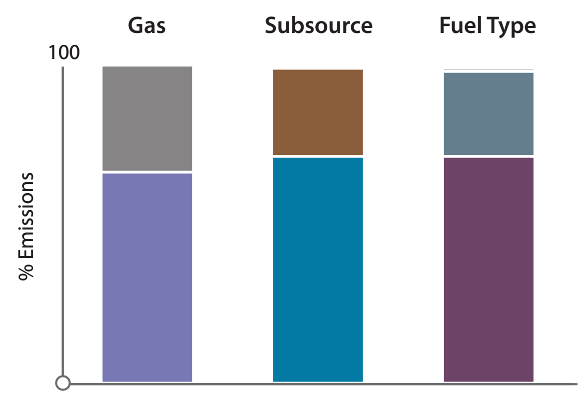
CH_4 and N_2O emissions result from the combustion of fossil fuels and biomass[26] in both stationary and mobile sources.[27] CH_4 emissions are primarily a function of the CH_4 content of the fuel and the overall combustion efficiency. N_2O emissions vary according to the type of fuel, combustion technology, size and vintage (model year for mobile combustion), pollution control equipment used, and maintenance and operating practices. Although fossil fuels are used as the primary energy source in most countries, biomass is an important energy source in developing countries where it is primarily used in small-scale combustion devices for heating, cooking, and lighting purposes.

Historical Trends

Between 1990 and 2015, CH_4 and N_2O emissions from fuel combustion increased by 36% as total fuel consumption increased by 53% on a BTU basis.[28,29] Global trends in fuel consumption are largely related to historical trends in energy demand. Global demand for electricity has increased, which resulted in an increase in the use of fossil fuels and biomass for power generation. Emissions from fossil fuel combustion in stationary and mobile sources increased by 57% from 1990 through 2015, while emissions from biomass combustion increased by only 7% over this time period. Fossil fuels have continued to dominate as the primary energy sources over non-fossil alternatives such as biofuels, waste energy, and traditional forms of biomass (i.e., wood fuel and charcoal).

2030 Emissions by Gas, Subsource, and Fuel Type

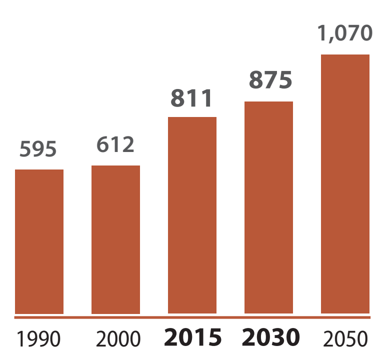
CH_4 emissions are projected to continue to make up the largest portion of combustion emissions by gas, increasing from 62% of total combustion emissions in 1990 to 67% in 2030. Fossil fuels are also projected to continue to make up the majority of combustion emissions, increasing from 59% of total combustion emissions in 1990 to 72% in 2030.[30]



Projected Emissions & Top Emitting Countries

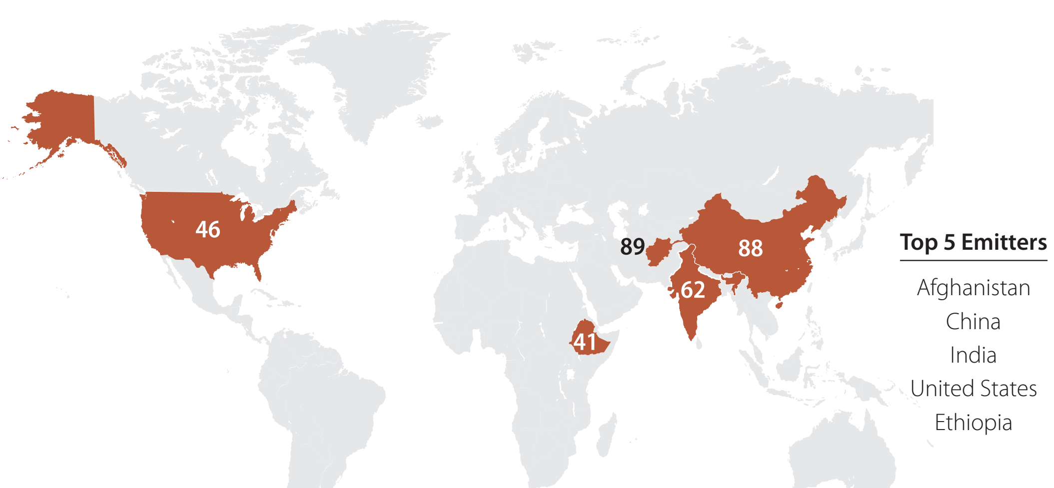
Emissions ($MtCO_2e$)

From 2015 through 2030, total non-CO_2 emissions from fuel combustion are projected to increase by 8%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 548 $MtCO_2e$



Top 5 Emitters

Afghanistan
China
India
United States
Ethiopia

Key Points

- The projected 8% increase in total combustion emissions from 2015 through 2030 is primarily driven by higher demand for fossil fuel energy due to economic and population growth.
- Increased access to electricity, development of urban areas, and industrialization in developing countries reduce reliance on traditional biomass to produce energy and increase fossil fuel use.
- Although biofuels such as ethanol and biodiesel continue to make up a small portion of the global energy supply, the use of these fuels in electric power and transportation activities is expected to increase by 33% from 2015 through 2030.[31]

Projected Trends

From 2015 through 2030, emissions from fossil fuel combustion are projected to increase by 15%, while emissions from biomass combustion are projected to decrease by 6%. This BAU projection assumes a 9% increase in global fossil fuel consumption over the projection period.

The growth in stationary fossil fuel combustion is primarily due to increased electricity consumption in non-Organisation for Economic Co-operation and Development (OECD) countries as a result of strong economic growth and rising standards of living.[32] The growth in transportation energy demand is also related to economic growth,[33] though improvements in combustion technologies and pollution controls have decreased transportation's emission intensity. Unlike CO_2 emissions, CH_4 and N_2O emissions from combustion are highly dependent on combustion conditions and not directly proportional to fuel quantities combusted.[34]

Declining use of traditional biomass in developing countries because of increased electricity access, urbanization, and industrialization drives the decline in biomass combustion emissions. Fossil fuel consumption in developing countries is projected to displace traditional forms of biomass energy, which are less versatile and less responsive to rapid consumption demand increases.[35]

Emissions from biofuels such as ethanol and biodiesel are projected to increase by 19% from 2015 through 2030 because of biofuels' increased use in electric power and transportation. Despite significant growth, emissions from biofuels are expected to contribute to just 1% of total combustion emissions in 2030.

The non-OECD Asia region is set to play an increasingly important role in global energy markets because of significant economic and population growth.[36] Continuing urbanization and industrialization of countries in this region will result in less reliance on traditional biomass for energy production and increased use of fossil fuels.

This analysis did not model mitigation options for reducing non-CO_2 GHGs from fossil fuel or biomass use; more complete combustion from higher efficiency engines and emission control devices can reduce emissions from combustion. Efficient cookstoves may have similar outcomes for combustion of wood and charcoal.

INDUSTRIAL PROCESSES

Introduction

The industrial processes sector is the fourth largest contributing sector to global emissions of non-CO_2 GHGs, accounting for 10% of emissions in 2015. This section presents global N_2O and F-GHG (SF_6, PFCs, SF_6, and NF_3) historical and projected emissions and mitigation potential from the industrial processes sector. F-GHGs are important because the gases tend to have large heat-trapping capacities and long atmospheric lifetimes. The sources covered in the chapter include the following categories:

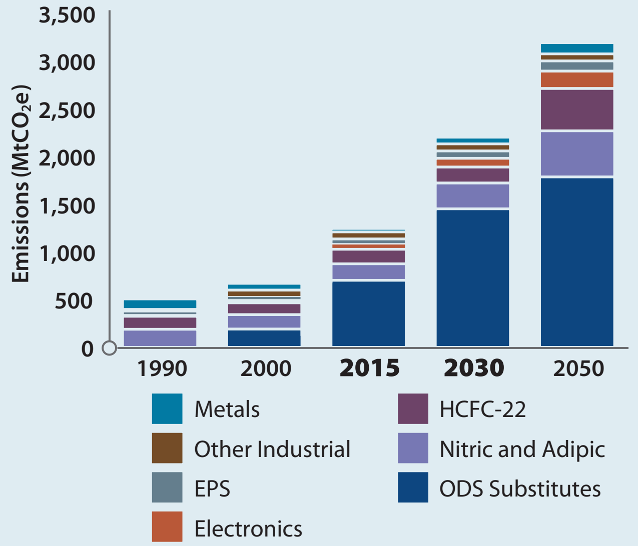
- Nitric and adipic acid production (N_2O)
- Electronics (HFCs, PFCs, SF_6, NF_3)
- Electric power systems (EPS) (SF_6)
- Metals (PFCs, SF_6)
- Substitutes for ozone-depleting substances (ODSs) (HFCs)
- HCFC-22 production (HFCs)

Projections and MAC curves were estimated for all sectors. These sources represent 94% of the total non-CO_2 GHG emissions in 2015 from the industrial processes sector.

Emissions from the industrial processes sector increased 145% between 1990 and 2015. ODS substitutes and HCFC-22 production were the largest sources of emissions in the industrial processes sector in 2015, comprising 56% and 12% of emissions, respectively. Nitric and adipic acid production accounted for 37% of non-CO_2 emissions from the sector in 1990 and decreased to 14% in 2015 because of the widespread installation of abatement equipment.

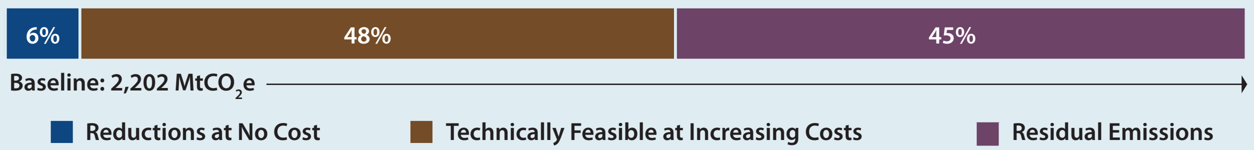
As the fastest growing sector, industrial processes' emissions are projected to increase 76% between 2015 and 2030 under a BAU scenario, reaching 2,202 $MtCO_2e$ in 2030. Emissions from ODS substitutes and HCFC-22 production are projected to increase 106% and 10% between 2015 and 2030, respectively. Emissions from ODS substitutes (HFCs) are projected to increase rapidly because of the phaseout of ODSs under the Montreal Protocol and strong predicted growth in traditional ODS applications (e.g., ref/AC). Although some countries have ratified amendments to the Montreal Protocol whose implementation would result in lower emissions, the BAU projections included here do not assume reductions from those amendments.

Historical and Projected Emissions from the Industrial Processes Sector



Mitigation potential from the industrial processes sector is estimated to be approximately 1,060 $MtCO_2e$ in 2030. This mitigation potential is 55% of the industrial processes sector's emissions and 28% of total global non-CO_2 mitigation potential in that year.

Emission Reduction Potential, 2030



Nitric and Adipic Acid Production

Source Background

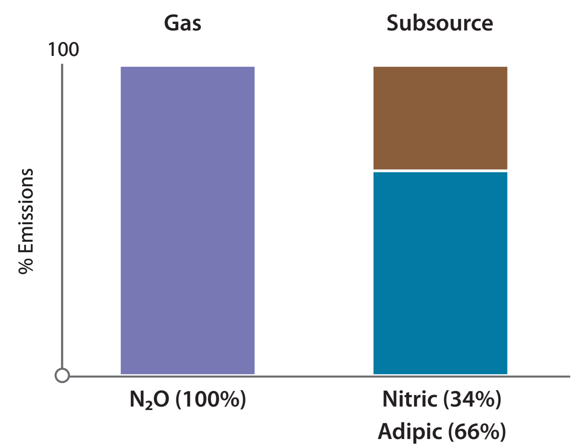
Nitric acid is an inorganic compound used primarily to make synthetic commercial fertilizer. Adipic acid is a white crystalline solid used as a feedstock in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. The production of these acids results in N_2O emissions as a by-product.

Historical Trends

N_2O emissions from nitric and adipic acid production decreased by 28% between 1990 and 2010. However, emissions increased by 27% between 2010 and 2015. Over the entire historical period, the production of both acids increased. Despite the production increase, emissions have historically declined due to worldwide installation of abatement technologies in the adipic acid industry.[37] As of 2016, most producers of adipic acid had implemented abatement technologies, but less progress has been made in abating emissions from nitric acid plants.[38] This analysis incorporated abatement to the extent that emission reductions are reflected in country-reported data. In addition, this analysis incorporated known bio-based adipic acid capacity until 2007, after which the capacity was maintained at a constant level.[39] The upward trend in emissions between 2010 and 2015 is primarily a result of an increase in adipic acid production without N_2O abatement in China.[40,41]

2030 Emissions by Gas and Subsource

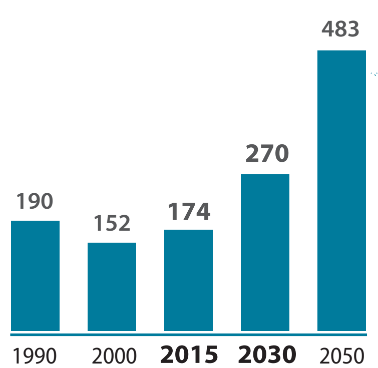
By 2030, about two-thirds of N_2O emissions from this source category are projected to be from adipic acid production compared with about one-third from nitric acid production.[42]



Projected Emissions & Top Emitting Countries

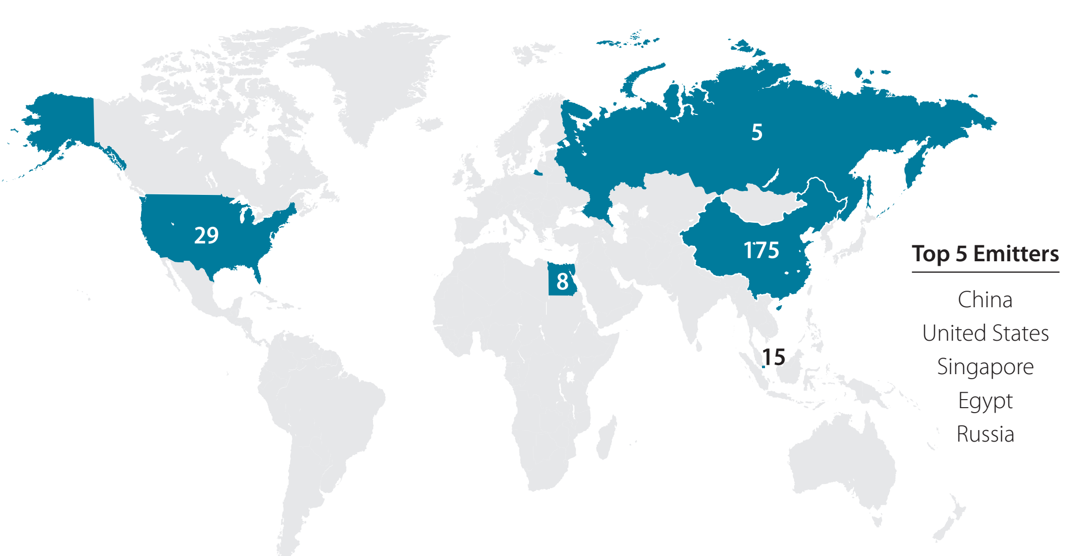
Emissions (MtCO$_2$e)

From 2015 through 2030, global N_2O emissions from nitric and adipic acid production are projected to increase by 55%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 37 MtCO$_2$e



Top 5 Emitters

China
United States
Singapore
Egypt
Russia

Key Points

- While nitric and adipic acid production increased at an annualized rate of 1% globally between 1990 and 2015, N_2O emissions from production decreased by 9%, primarily due to worldwide installation of abatement technologies in the adipic acid industry.
- Global N_2O emissions from nitric and adipic acid production are projected to increase by 55% between 2015 and 2030, driven by projected high growth in adipic acid demand.
- Emission projections from adipic acid production incorporate fixed historical emission control.

Projected Trends

Because a small number of countries produce nitric and adipic acid, the top 5 emitting countries comprise 86% of global emissions in 2030. China is expected to contribute the most emissions from nitric and adipic acid production by 2030, followed by the United States and Singapore. Key factors influencing the overall increasing trend from 2015 through 2030 include (1) high projected growth in the global demand for adipic acid, (2) increasing emissions from production in China, (3) decreasing proportion of emissions from OECD countries due to decreasing proportion of production in OECD countries, and (4) capacity expansions to meet increased global demand for adipic acid in Asia, while market restructuring from reduced consumption and market saturation in Western Europe and North America.[43]

Emissions from nitric acid production are estimated to increase by 17% between 2015 and 2030, which aligns with the estimated 16% growth of nitric acid production. Emissions are projected based on estimated long-term nitrogenous fertilizer consumption, broken out by world regions for 2015 through 2030.[44] Literature suggests that to meet projected food demand the production of nitrogenous fertilizer will increase between 70% and 100% by 2050 compared with 2000 production.[45]

N_2O abatement in nitric acid plants is rarely implemented without incentive programs; therefore, this analysis did not assume that any abatement technology was already installed.[46] Fertilizer production and consumption are expected to continue to increase in Asia and decline in Europe and North America.[47] The decline is due in part to strict regulations stemming from concerns about nitrates in the water supply.

From 2015 through 2030, emissions from adipic acid production are estimated to increase by 86%, which aligns with the estimated 87% growth of adipic acid production. Emission projections incorporate fixed historical emission control, which includes historical bio-based adipic acid production and N_2O emission abatement to the extent that emission reductions are reflected in country-reported data. The main driver for the projections is the BAU assumption that global adipic acid consumption will increase by 3.5% annually from 2015 through 2030, based on the consumption growth rate for the period 2008 through 2013. The growth rate of 3.5% was used because it reflects the average of the range of growth rate projections in the literature.[48,49,50,51]

Nitric and Adipic Acid Production

Key Points

- **The global abatement potential is 231 $MtCO_2e$, or 86% of projected emissions in 2030.**
- **All mitigation potential for this source category comes at a cost higher than \$0 $MtCO_2e$. A 69% reduction in emissions is achievable at prices below \$20.**
- **Facility design constraints and/or operating costs drive abatement measure selection.**
- **Thermal destruction is the technology with the most mitigation potential.**

Abatement Measures

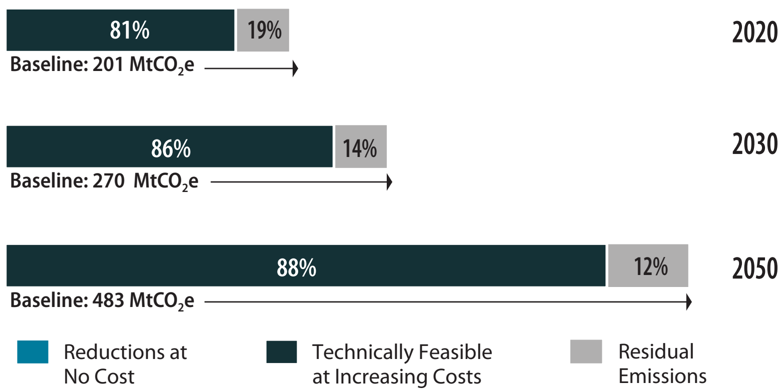
To estimate abatement potential for this analysis, we used a modified version of the projected emissions. This revised baseline projection assumes a higher N_2O emissions from nitric acid production and a smaller share of emissions attributed to adipic acid production.

This analysis considered four abatement measures applied to the chemical process used to produce nitric and adipic acid to reduce the quantity of N_2O emissions released during production. Three abatement measures—catalytic decomposition, catalytic reduction, and homogeneous decomposition—were modeled for nitric acid production. Catalytic decomposition and reduction can be applied as tertiary measures. Catalytic and homogeneous decomposition are considered secondary processes, which are applied inside or immediately following the ammonia burner. Homogeneous decomposition is better suited for new facilities because of the associated design changes and capital costs. Some primary measures, which are applied at the beginning of the production process to prevent the formation of N_2O, exist, but they were not modeled in this analysis because of data limitations.

Adipic acid facilities direct the flue gas to a reductive furnace in a thermal destruction process to reduce nitric oxide (NO_X) emissions. Thermal destruction is the combustion of off-gases (including N_2O) in the presence of CH_4. The combustion process converts N_2O to nitrogen, resulting primarily in emissions of NO and some residual N_2O.[52] The heat generated from this process can also be used to produce process steam, offsetting more expensive steam generated using just fossil fuels.

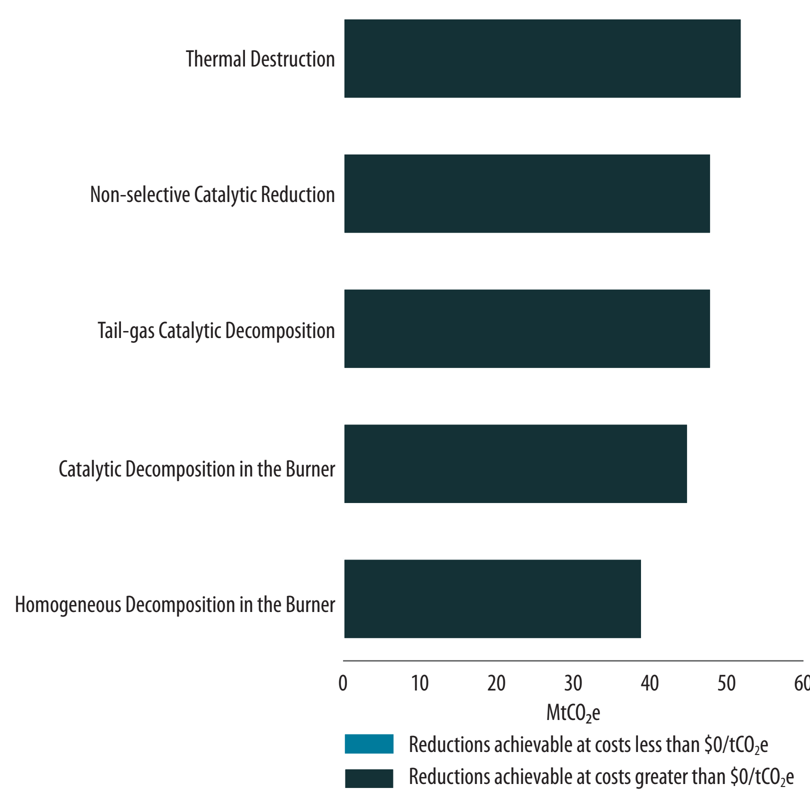
Total Reduction Potential

There are no emission reductions available in nitric and adipic acid production at prices below \$0/tCO_2e. At increasing costs, an 81% reduction in emissions is available in 2020. The emission reduction potential at increasing costs rises to 86% in 2030 and to 88% in 2050.



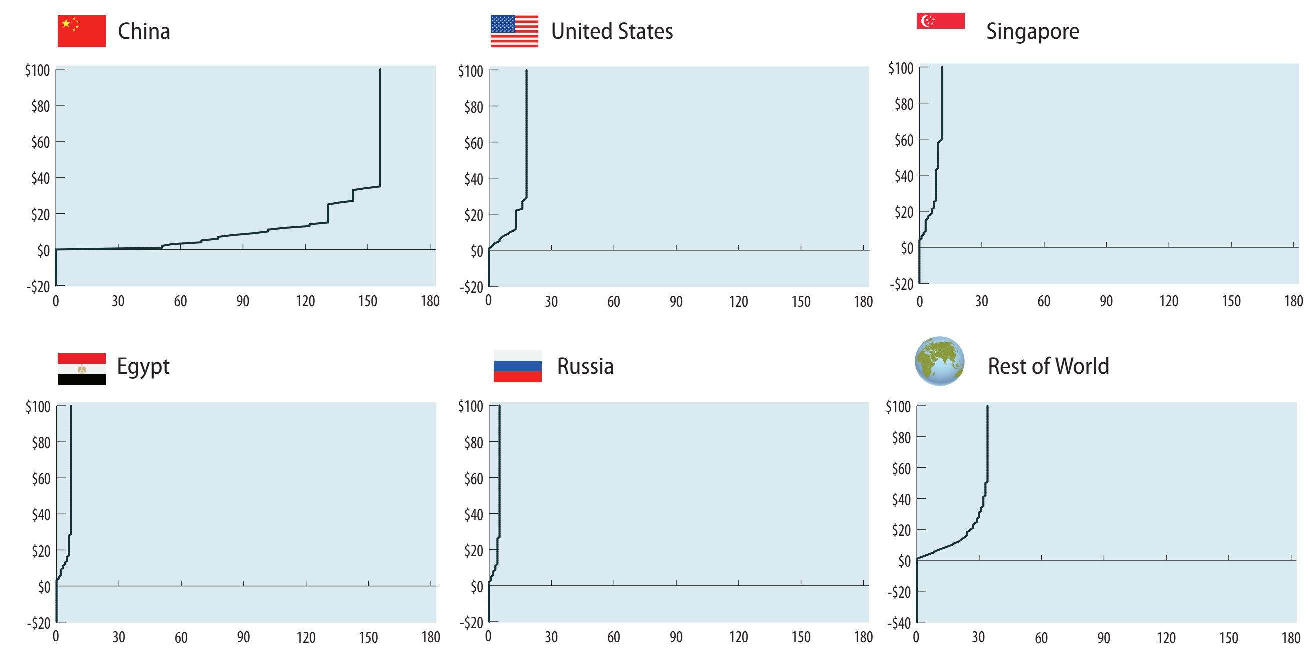
Reduction Potential by Technology

In 2030, thermal destruction is the leading emission abatement measure with 52 $MtCO_2e$, though all abatement measures offer at least 39 $MtCO_2e$ of potential abatement. There is no potential abatement below a price of \$0/tCO_2e.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.



Abatement Potential

The global emission reduction potential in the nitric and adipic acid production source category is 231 $MtCO_2e$ in 2030, or 86% of projected baseline emissions from nitric and adipic acid production. Roughly 80% of the abatement potential is achievable at break-even prices between \$0 and \$20, demonstrating that low break-even prices can have a substantial impact on reducing emissions from this source category.

In 2030, the top 3 mitigation technologies at the global level are thermal destruction, tail-gas catalytic decomposition, and nonselective catalytic reduction. The top 3 technologies contribute to 64% of the global mitigation potential. Thermal destruction, the top technology, contributes to nearly a quarter of the source category's overall potential.

At the country level, China, the United States, and Singapore are the largest emitters in this source category, making them the largest potential sources of abatement as well. The top 3 countries combined contribute to 80% of the global abatement potential in 2030, or 184 $MtCO_2e$. China alone causes over 65% of emissions from nitric and adipic acid production but also contributes to 67% of the global abatement potential. China and the United States can reach 61% and 49% of their national abatement potential at break-even prices below \$10/tCO_2e.

Although a comprehensive inventory of nitric acid production facilities is not available, adipic acid production is more clearly characterized. In the 1990s, most of the adipic acid producers in developed countries voluntarily adopted N_2O abatement measures.[53,54,55] In 2005, with the establishment of the Clean Development Mechanism (CDM) methodology for crediting N_2O abatement projects at adipic acid plants, producers in developing countries began to adopt N_2O abatement measures. As of 2010, 85% of the adipic acid production capacity globally already had N_2O emission controls in place. Of the remaining 15% uncontrolled capacity, 12% resides in China, and the rest is distributed between Japan, Ukraine, and India.

Electronics

Semiconductor, FPD, and PV Manufacturing

Source Background

Electronics consists of emissions from the manufacturing of semiconductors, flat panel displays (FPDs), and photovoltaics (PV). During the manufacture of these electronics, F-GHGs, including HFCs, PFCs, SF_6, and NF_3, are emitted from two repeated activities: (1) cleaning of chemical vapor deposition chambers and (2) plasma etching (etching intricate patterns into successive layers of films and metals).

Historical Trends

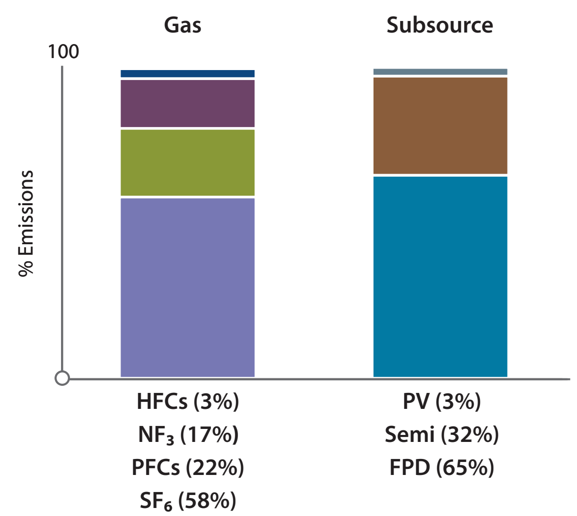
Between 1990 and 2015, emissions from electronics manufacturing increased by 519%. During the same time frame, semiconductor manufacturing emissions increased by 149%, because of rapid growth in demand for electronics. Emission growth would have been larger without the application of abatement measures and country- and global-level reduction agreements.

Emissions from FPD manufacturing increased by over 12,000% between 1990 and 2015. Underlying this growth in emissions from electronics manufacturing, FPDs have grown from a very small portion to over half of the electronics display market.

Because of the nascence of the PV industry before 2005, emissions from PV manufacturing were only estimated after 2005. From 2005 through 2015, emissions from PV manufacturing increased by over 2,000%. The increase in emissions from PV manufacturing is due to growth of the PV industry from a nascent to mature industry as demand for renewable sources of energy has increased.

2030 Emissions by Gas and Subsource

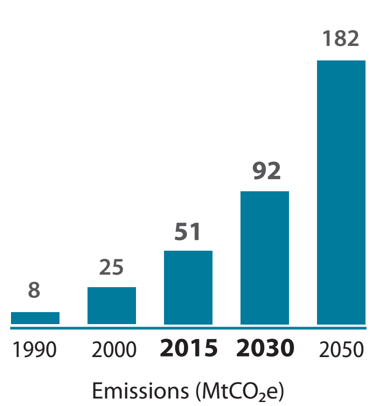
In 2030, FPD manufacturing is projected to contribute nearly 65% of emissions from this category, followed by semiconductor manufacturing (32%) and PV manufacturing (3%). In 2030, emissions from SF_6 are projected to represent approximately 58% of emissions from this category followed by PFCs (22%), NF_3 (16%), and HFCs (3%).



Projected Emissions & Top Emitting Countries

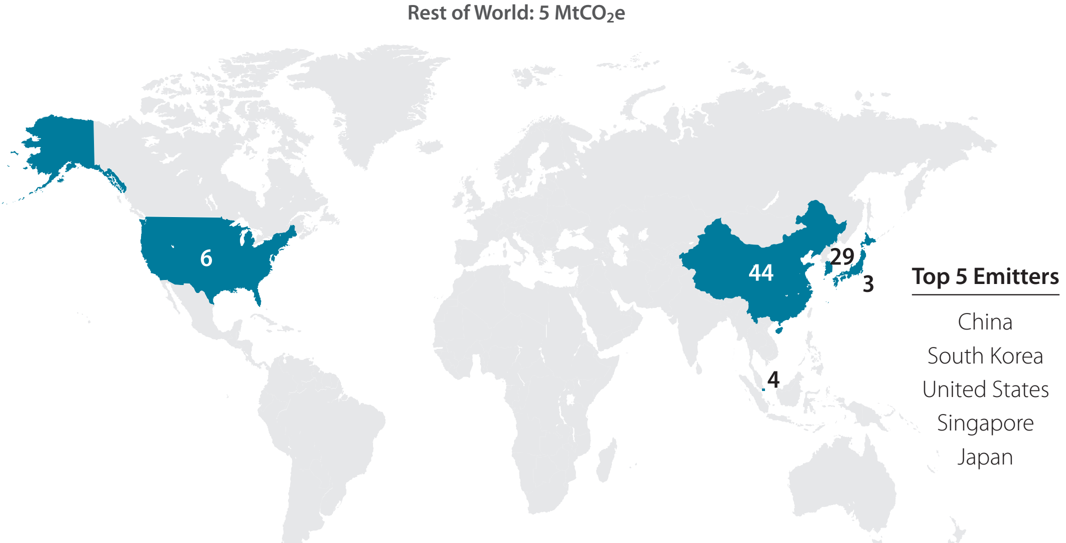
Emissions ($MtCO_2e$)

From 2015 through 2030, F-GHG emissions from electronics manufacturing are projected to increase by 80%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 5 $MtCO_2e$



Key Points

- **From 1990 through 2015, emissions from electronics manufacturing increased by 519% because of the rapid growth in the demand for electronics.**
- **From 2015 to 2030, emissions are estimated to increase by 80%, driven by increased demand for electronics and the increasing market share of FPDs.**
- **Emissions from PV manufacturing are expected to decrease between 2015 and 2030 because of the slowed growth in global installed solar generating capacity, though these estimates depend heavily on country-level policies, which may change significantly in the future.[56]**

Projected Trends

From 2015 through 2030, emissions from FPD manufacturing are estimated to triple. This projection assumes large growth in the FPD industry, tapering from an assumed annual growth rate of about 9% from 2015 through 2025 to about 4% from 2025 through 2050. Long-term industry forecasts show continued growth in demand[57] driven by demand for larger displays, but growth is expected to slow down after 2025, with the maturity of FPD applications and a slowing trend toward larger size screens.[58]

From 2015 through 2030, emissions from semiconductor manufacturing are estimated to increase by 46% primarily because of the increased demand for electronic goods. The projected emission results continue to be driven by emissions from China, whose country share grows from its historical status of about 30% of global emissions in 2015 to closer to 50% by 2030.

Manufacturing capacities are projected to increase at a rate equivalent to the growth in each country's gross domestic product. Gas shares by country (e.g., percentage of a country's semiconductor manufacturing emissions that are a certain gas, such as SF_6) were calculated from the historical reported emissions of total semiconductor emissions. These gas shares were held constant from 2015 through 2030 to determine country emissions by type of gas. Gas shares may be affected by advancements in abatement technology, but these projections maintain the gas shares as constant because of the inability to predict these changes.

Projected emissions from the solar PV industry decrease by 72% from 2015 through 2030. Projected emissions are expected to drop drastically in 2020 (58% decrease from 2015) and 2025 (42% decrease from 2020) and then become relatively more stable from 2030 through 2050. Decreasing trends in emissions are a result of a slowed growth rate in installed solar capacity (i.e., the incremental change in the installed solar generating capacity). The projected world installed solar generating capacity is expected to grow by 44.5 gigawatts (GW) in 2015 but only by 19.5 GW in 2016 (and then fluctuates between 10.4 GW and 19.5 GW from 2016 through 2040).[59] However, these estimates depend heavily on changes in country-level policies; what these policies will look like and how they will be implemented are still unknown.[60]

Electronics

Semiconductor, FPD, and PV Manufacturing

Key Points

- **The global abatement potential for the electronics source category is 51 $MtCO_2e$, or 56% of baseline emissions, in 2030.**
- **Mitigation potential from FPD manufacturing has the greatest reduction potential at 41 $MtCO_2e$ in 2030, 44% of baseline emissions.**
- **Reducing emissions from these sources is expensive: break-even prices below $20/$tCO_2e$ can achieve only a 1% reduction in baseline emissions.**

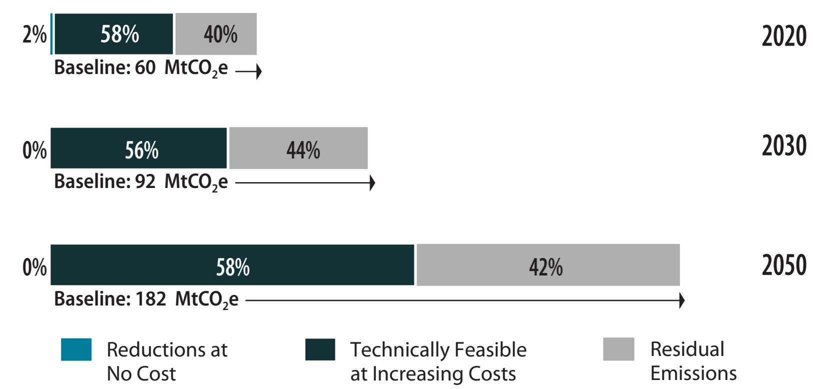
Abatement Measures

Abatement measures can be applied in the electronics source category throughout processes for the manufacturing of semiconductors, FPDs, and PVs. This analysis considered eight abatement measures across the two manufacturing processes: central abatement, thermal abatement, catalytic abatement, plasma abatement, catamal abatement, NF_3 remote chamber cleaning, gas replacement, and process optimization. These technologies reduce emissions from either etch or chamber-cleaning processes (or in some cases both). The measures focus on reducing F-GHG (i.e., HFCs, PFCs, SF_6, or NF_3) emissions that are released during production.

Across the technologies used in the electronics manufacturing industry, thermal abatement, NF_3 remote chamber cleaning, and catalytic abatement tend to have the highest market penetration, meaning that manufacturers are implementing these abatement technologies most often. These technologies have high reduction efficiencies. Thermal abatement and NF_3 remote chamber cleaning have a reduction efficiency of 95%, while catalytic abatement has a reduction efficiency of 99%. Both thermal and catalytic abatement destroys or removes F-GHGs from effluent process streams; one uses heat and the other uses catalysts (e.g., CuO, ZnO, Al_2O_3). Thermal and catalytic abatement technologies have a lifetime of approximately 7 years. In contrast, a facility can use NF_3 remote chamber cleaning between 21 and 25 years before needing replacement.

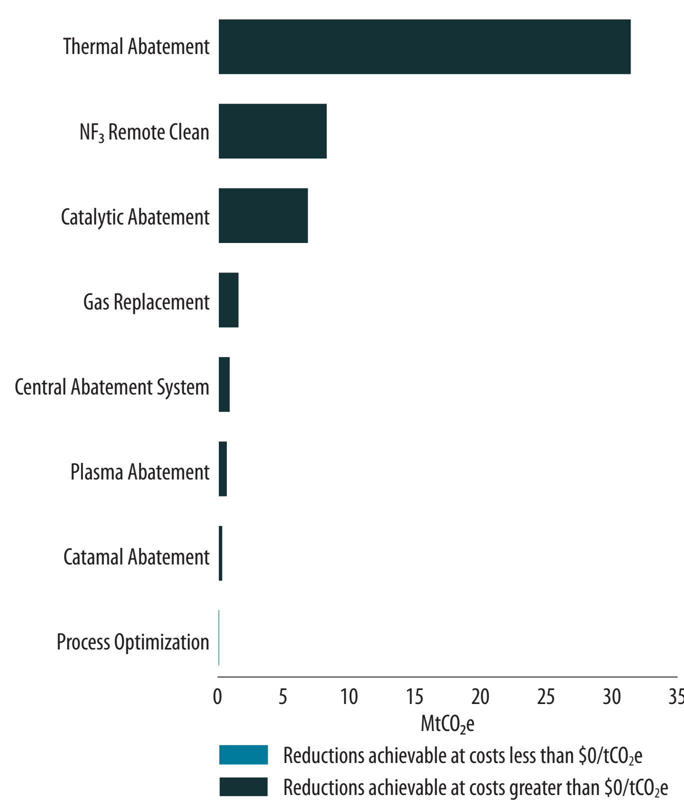
Total Reduction Potential

Reducing emissions by 2% compared with the 2020 baseline is cost-effective (below $0/$tCO_2e$). An additional 58% reduction is available using technologies with increasingly higher costs.



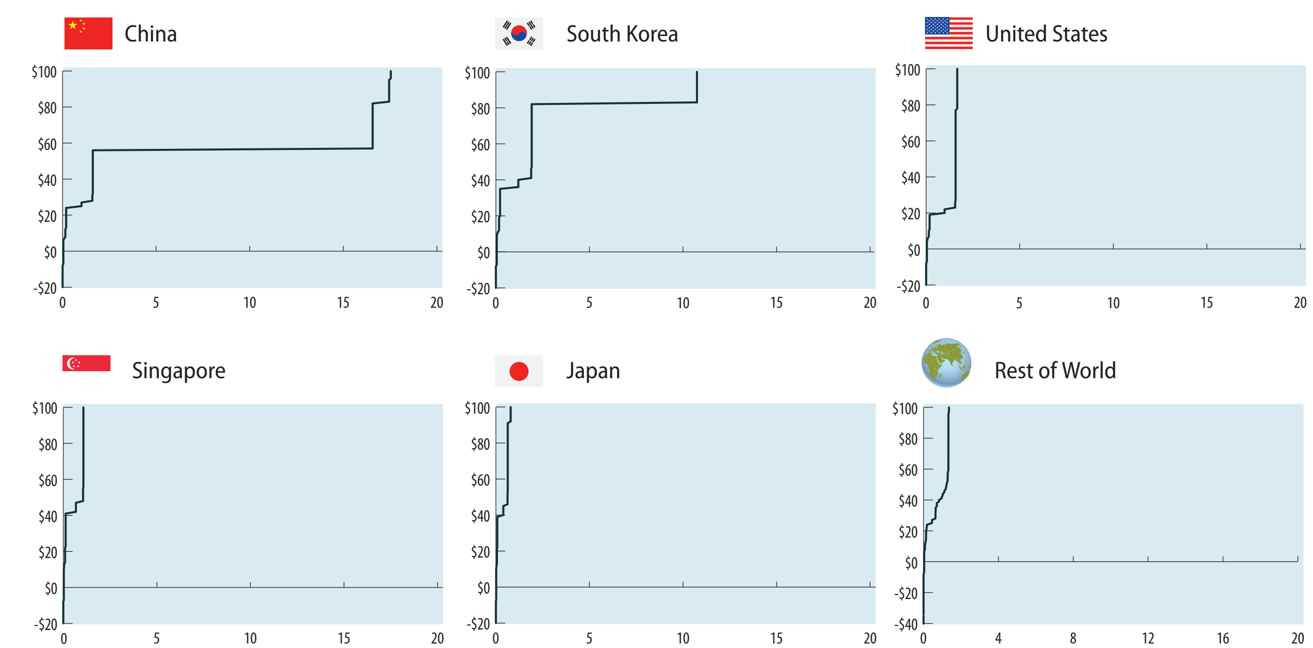
Reduction Potential by Technology

In 2030, no abatement is available below $0/$tCO_2e$. For costs greater than $0/$tCO_2e$, thermal abatement is the leading emission abatement measure with the potential to reduce emissions by 32 $MtCO_2e$ in 2030.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of baseline emissions represent 96% of all potential global abatement in the electronics source category in 2030. China is the highest emitting country but also contributes to 55% of global abatement potential for the category, or 28 $MtCO_2e$, in 2030.



Abatement Potential

Abatement potential in the electronics source category is estimated to be 51 $MtCO_2e$, 56% of the baseline emissions. Implementing abatement measures in the electronics source category is costly. At break-even prices below $20/$tCO_2e$, only 1% of baseline emissions can potentially be abated in 2030, which is equal to 2% of the annual potential abatement.

FPD manufacturing has the highest abatement potential followed by semiconductors and PV. The technologies with the highest abatement potential are thermal abatement and NF_3 remote chamber cleaning, which have the potential to mitigate 32 $MtCO_2e$ and 8 $MtCO_2e$, respectively, at costs greater than $0/$tCO_2e$. Thermal abatement constitutes 62% of the abatement potential, and NF_3 remote chamber cleaning contributes to 17%. Installing these abatement technologies requires high initial capital costs and annual maintenance costs. As a result, emission reductions from the electronics source category are not cost-effective. For example, installing thermal abatement measures costs $6.3 million and has annual maintenance costs of $360,000.

China, South Korea, and the United States have the highest abatement potential in the electronics source category in 2030. China has the potential to abate 28 $MtCO_2e$, which is 55% of the global abatement potential. South Korea's abatement potential reaches 17 $MtCO_2e$ followed by 2 $MtCO_2e$ for the United States. The leading abatement technologies in all three countries follow the global trend; thermal abatement is the number one abatement measure followed by NF_3 remote chamber cleaning. Thermal abatement can potentially mitigate 17 $MtCO_2e$, 10 $MtCO_2e$, and 1 $MtCO_2e$ in China, South Korea, and the United States, respectively.

Electric Power Systems

Source Background

SF_6 is used for absorption of energy from electric currents flowing between conductors and as an insulating medium in electrical transmission and distribution equipment (also referred to herein as electric power systems). SF_6 emissions occur through leakage and handling losses. Manufacturing equipment for electrical transmission and distribution also results in SF_6 emissions, but this report does not include this source.

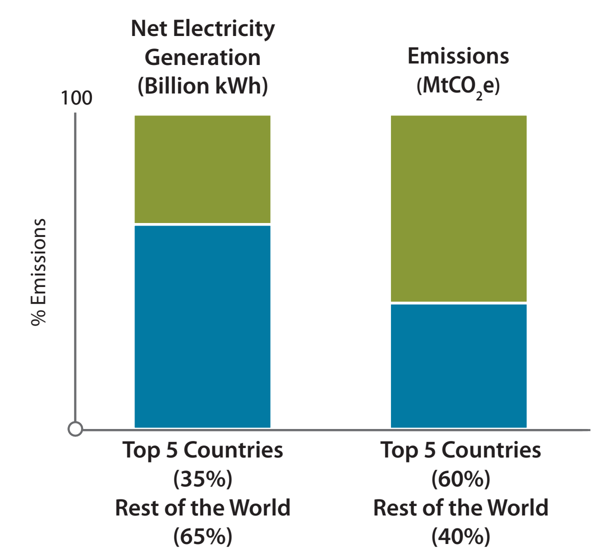
The type and age of SF_6-containing equipment and the handling and maintenance protocols used by electric utilities affect SF_6 emissions from electric power systems. Historically, approximately 20% of total global SF_6 sales have been attributed to electric power systems, where the SF_6 is believed to have been used primarily to replace emitted SF_6. 60% of global sales have gone to manufacturers of electrical equipment, where the SF_6 is believed to have been mostly banked in new equipment.[61]

Historical Trends

Global emissions increased by 22% from 1990 through 2015 despite a downward trend in the mid-1990s when the price of SF_6 gas increased significantly, motivating electric utilities to improve SF_6 management practices. In the following decade as SF_6 sales increased, that trend was reversed. The continued increase in global emissions occurred for all countries except for the United States, parts of the European Union, and Japan, where voluntary efforts to reduce emissions from electric power systems have had success.

2030 Activity Data and Emissions

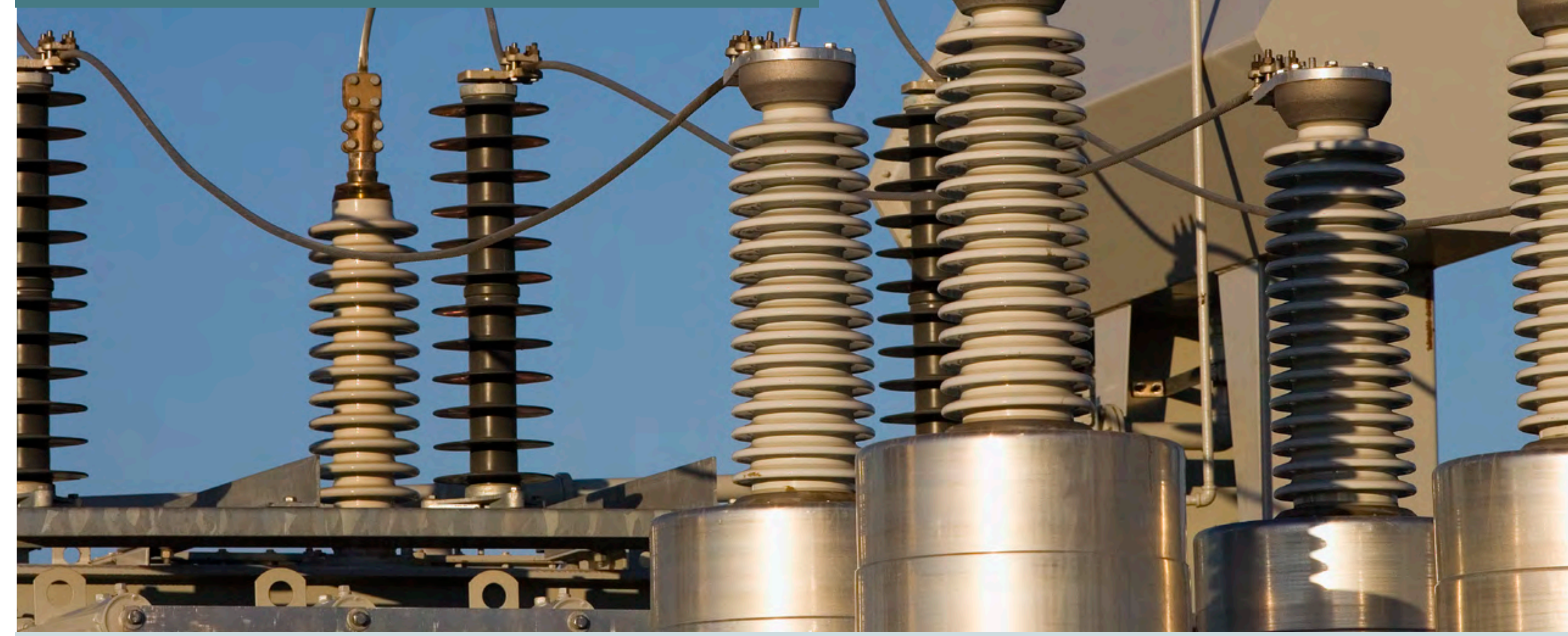
In 2030, the top 5 emitting countries comprise 60% of global SF_6 emissions from electric power systems and 35% of net electricity generation. As infrastructure expands, emissions from developing countries are anticipated to grow at the same rate as country- or region-specific net electricity generation projections.



*Top 5 based on top 5 highest emitting countries.

Key Points

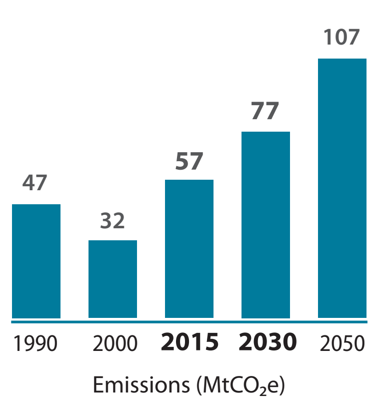
- **Overall, global SF_6 emissions increased by 22% from 1990 through 2015 despite a downward trend in the mid-1990s.**
- **Global SF_6 emissions are estimated to increase by 34% by 2030, driven by an expected increase in electricity usage in developing countries, particularly China.**
- **SF_6 emissions from developed countries are expected to decline as utilities, through ongoing involvement in government-sponsored programs, implement reduction measures.**



Projected Emissions & Top Emitting Countries

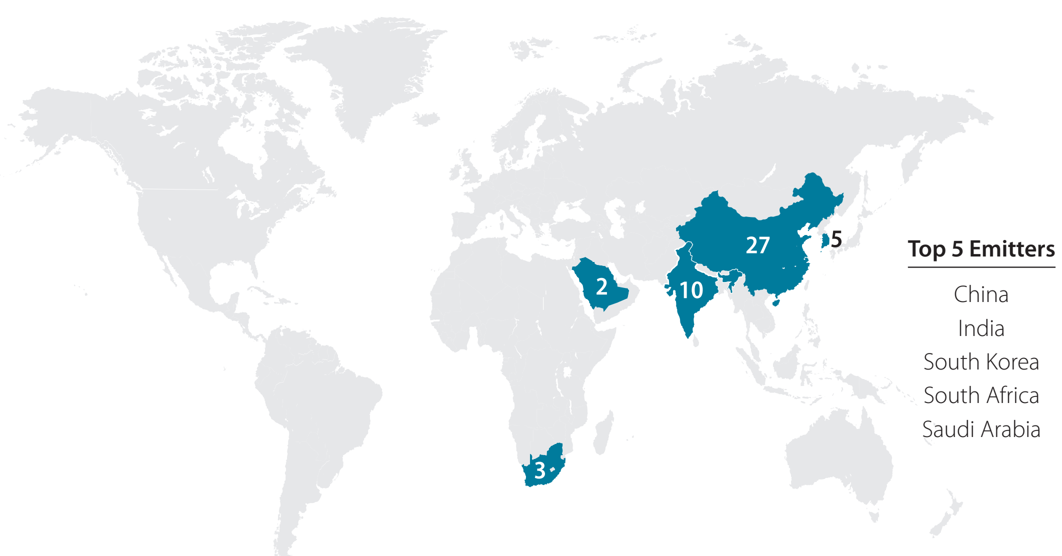
Emissions ($MtCO_2e$)

From 2015 through 2030, SF_6 emissions from electric power systems are estimated to increase steadily by 34%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 31 $MtCO_2e$

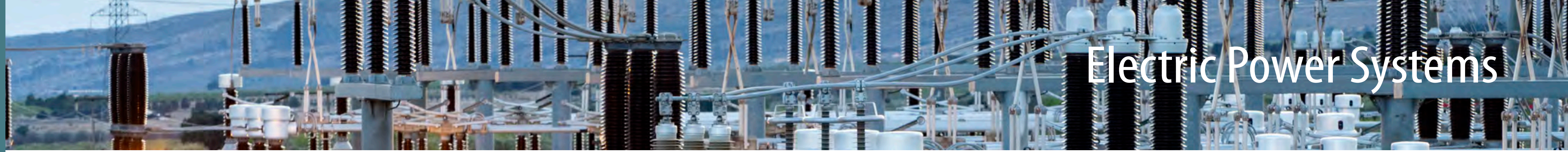


Projected Trends

From 2015 through 2030, SF_6 emissions from the operation of electric power systems are estimated to increase by 34%. Emissions from developing countries are expected to continue to increase over the projection period. 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, which is projected to increase twice as fast in developing countries between 2015 and 2030.[ii]

In contrast, in the United States and the European Union, emissions are expected to decrease between 2015 and 2030 as utilities continue to implement reduction measures in response to voluntary and mandatory programs. In addition, utilities in these countries are installing equipment with smaller SF_6 capacity, helping to minimize the potential for further emissions.

China's estimated emissions significantly contribute to the overall increasing emission trend. China has experienced and is expected to continue to experience a relatively high growth rate of SF_6 emissions.[62,63] Fang et al.[64] estimate that approximately 70% of China's total SF_6 emissions originate from the electrical equipment industry. While historical emissions from Fang et al. are relatively close to the EPA's historical estimate, the study's 2020 projection diverges significantly to nearly double the EPA's 2020 estimate.



Electric Power Systems

Key Points

- **The global abatement potential for electric power systems in 2030 is 54 $MtCO_2e$, or 70% of baseline emissions.**
- **The abatement potential at cost-effective prices ($0/$tCO_2e$) is estimated to be 10% of the electric power system's baseline in 2030, rising to 43% at prices below $20/$tCO_2e$.**
- **Improved SF_6 handling practices during decommissioning of electric power systems is the leading abatement measure.**

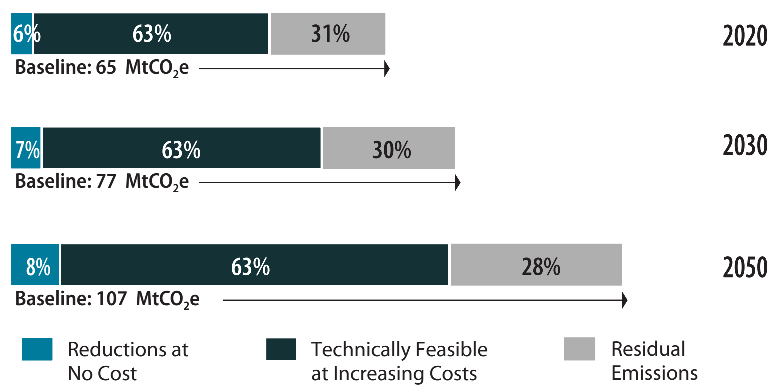
Abatement Measures

This analysis considers five main abatement technologies and measures for the electric power system. The first measure, SF_6 recycling, reduces emissions by technicians transferring SF_6 to special gas carts before maintenance or decommissioning to reuse the gas. The second measure, known as leak detection and repair reduces emissions in a two-step process: (1) identifying the leaks through either a camera or a hand-held gas detector and (2) later sealing the leak or completely replacing the broken component. The third measure, equipment refurbishment, is a method that reduces longer term leakage problems by disassembling and possibly upgrading equipment with clean or new components, but this abatement measure can be costly to implement. Another abatement measure uses a combination of different gases to form a class of g3 mixtures that have a GWP less than SF_6. The final and most cost-effective measure, especially in the developing world, is improving SF_6 handling. Properly training employees to handle SF_6 can reduce and avoid instances of accidentally venting the gas; using inappropriate fittings to connect transfer hoses to cylinders or equipment; and misplacing gas cylinders, which result in handling losses.

This analysis divided countries into partially controlled and uncontrolled systems. The United States, the European Union, and Japan comprise the controlled system, meaning that these nations have partially or fully adopted the available abatement technologies. In contrast, developing nations are categorized as uncontrolled systems because they do not frequently apply abatement options.

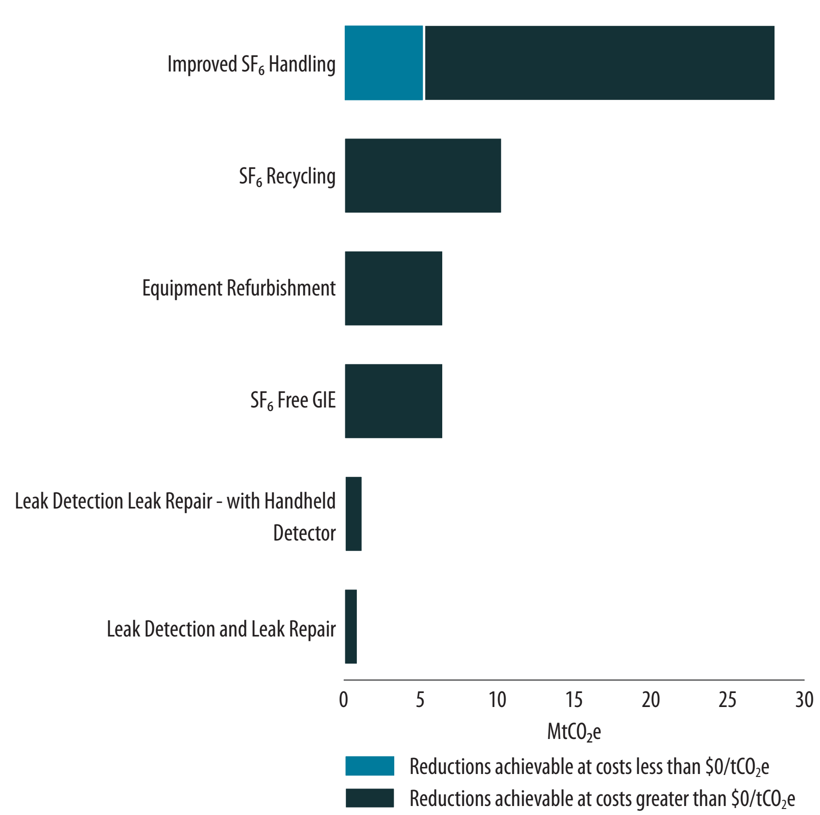
Total Reduction Potential

Reducing emissions by 6% compared with the 2020 baseline is cost-effective. The cost-effective reduction potential rises to 7% in 2030 and to 8% in 2050. An additional 63% reduction is available using technologies with increasingly higher costs (above $0/$tCO_2e$).



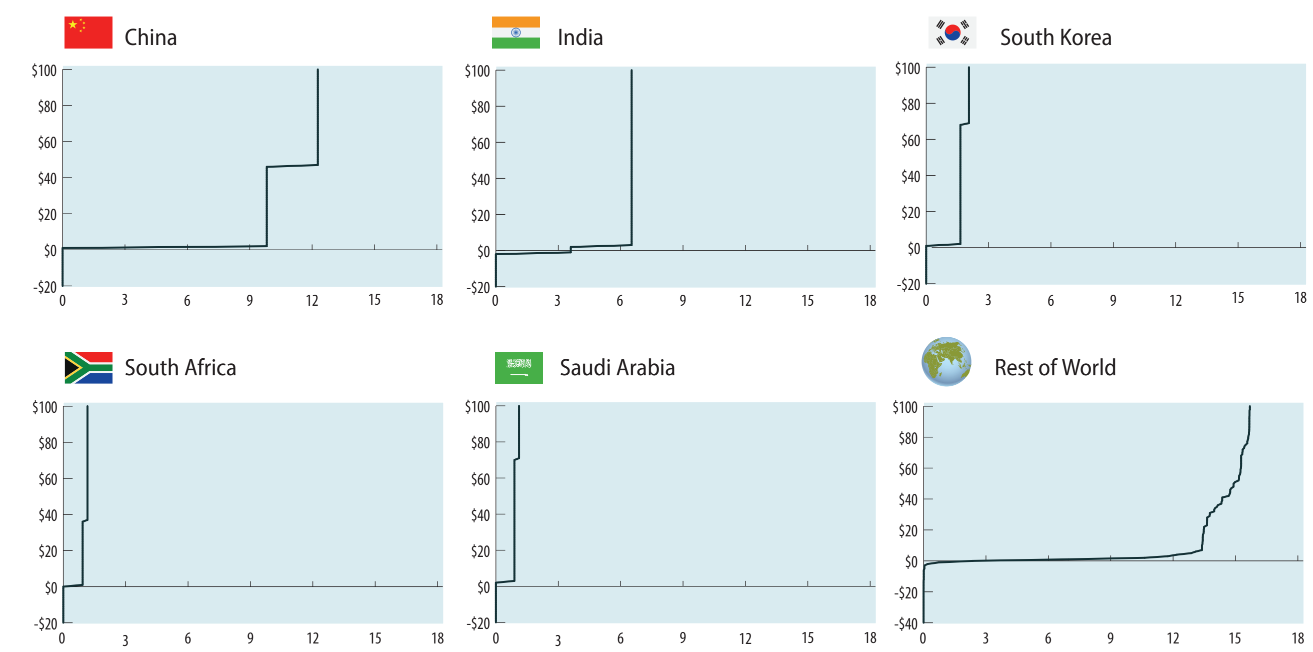
Reduction Potential by Technology

In 2030, improving SF_6 handling is the leading emission abatement measure, and 5.2 $MtCO_2e$ of reductions are achievable at prices below $0/$tCO_2e$. At prices greater than $0/$tCO_2e$, this measure can mitigate 23 $MtCO_2e$.



Marginal Abatement Cost Curves, 2030

China has the highest baseline emissions for the electric power systems source category in 2030, followed by India, South Korea, South Africa, and Saudi Arabia. China contributes to 34% of global abatement potential, and the top 5 emitters combined contribute to 60% of global abatement potential.



Abatement Potential

Significant reductions are available at a low cost in the electric power systems source category. For example, nearly 10% of abatement potential can be achieved at break-even prices less than $0/$tCO_2e$. Emission reduction technologies that cost up to $5/$tCO_2e$ can reduce emissions by 32 $MtCO_2e$, accounting for 60% of the technologically feasible emission reductions in 2030.

At the global level, improved SF_6 handling and SF_6 recycling offer the highest abatement potential in 2030. Improved handling can mitigate 28 Mt CO_2e and contributes to half of the source's potential in 2030. At break-even prices less than $0/$tCO_2e$, this measure makes up 10% of the annual estimated mitigation. Additionally, SF_6 recycling is estimated to mitigate 10 Mt CO_2e, or one-fifth of the annual potential in 2030. Although SF_6 recycling does not offer abatement with costs lower than $0/$tCO_2e$, the technology still offers monetary benefits. Not purchasing new gas and reducing emissions can provide up to $102,000 in annual revenues for an uncontrolled system.

China, India, and South Korea have the highest mitigation potential in 2030. China can mitigate 18 $MtCO_2e$ in 2030, or 34% of the global abatement potential. India's and South Korea's abatement potentials are estimated to reach 8 Mt CO_2e and 3 Mt CO_2e, respectively, or 14% and 6% of the electric power systems source category's overall potential. All three countries can achieve most of their potential at low costs. Half of India's potential is achievable at break-even prices lower than $0/$tCO_2e$, whereas the other two countries can reach half of their potential at break-even prices less than $5/$tCO_2e$. To reach these potentials, improving SF_6 handling is a crucial abatement measure. Making handling improvements can help each country reach between 48% and 54% of its annual mitigation potential in 2030.

Metals

Aluminum and Magnesium Production

Source Background

Emissions from metal production include PFCs emitted as by-products of aluminum production and SF_6 emitted from magnesium production.

During the aluminum smelting process, high voltage anode effect events emit tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). Recent research has shown that low-voltage anode effect events also emit PFCs;[65] however, such emissions are not accounted for in this analysis.

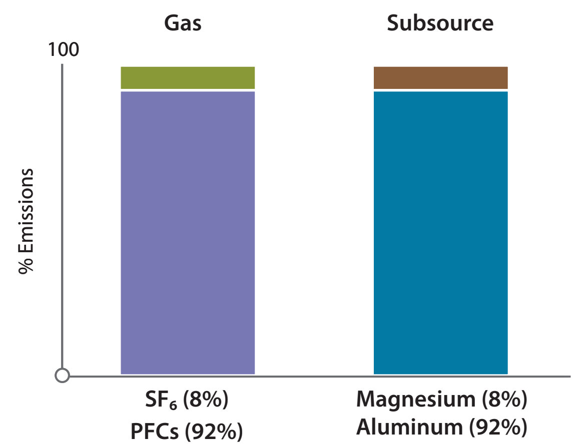
The magnesium production and casting industry uses SF_6 to prevent spontaneous combustion of molten magnesium in the presence of air. Fugitive SF_6 emissions occur mostly during primary production, die-casting, and recycling-based or secondary production. Additional processes may use SF_6; however, these processes are believed to be minor emission sources.

Historical Trends

From 1990 through 2015, combined PFC and SF_6 emissions from metal production decreased by 68%. Emissions from aluminum production declined by 67% as a result of global smelters voluntarily reducing emissions through improvements in smelter technologies and practices. From 1990 through 2015, global emissions from magnesium production decreased by 71%, due to the EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry, which formed a global industry commitment to eliminate SF_6 emissions from operations by the end of 2010.[66]

2030 Emissions by Gas and Subsource

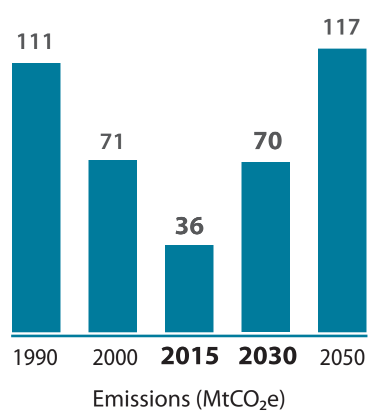
The vast majority of emissions from metal production are PFC emissions from aluminum production (92%), which consist of CF_4 and C_2F_6 emissions. CO_2 is also generated from anode consumption during aluminum production, but CO_2 emissions are outside the scope of this analysis. Magnesium production results in SF_6 emissions.



Projected Emissions & Top Emitting Countries

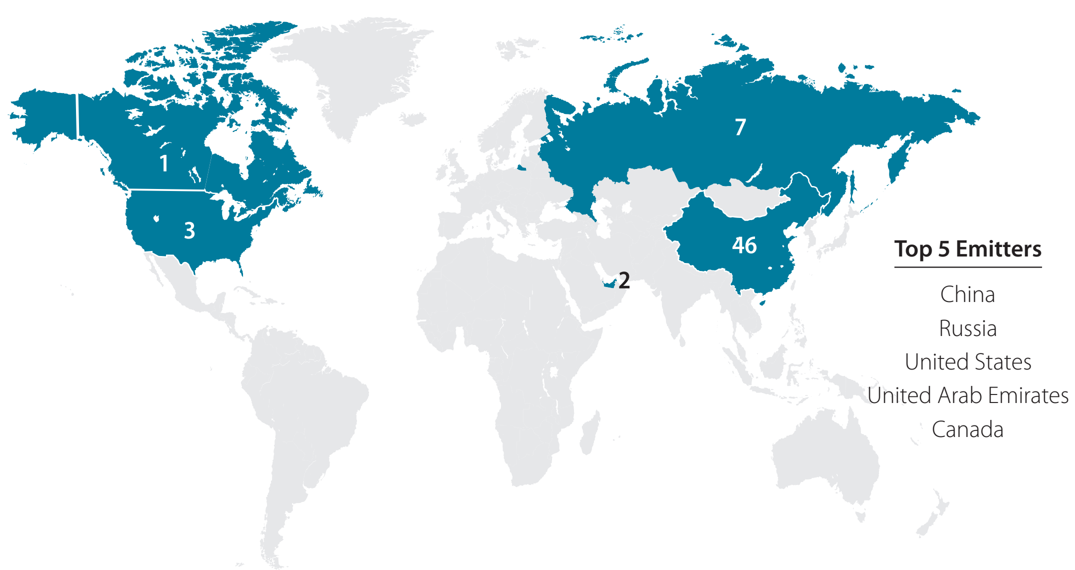
Emissions ($MtCO_2e$)

From 2015 through 2030, combined emissions from metal production are projected to almost double.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 11 $MtCO_2e$



Key Points

- **Emissions from metal production are projected to increase by 96% between 2015 and 2030, with varying growth across emissions from aluminum production (103% increase) and magnesium production (40% increase).**
- **Aluminum and magnesium production are projected to increase by 42% and 40%, respectively, from 2015 through 2030, driving the increase in overall emissions.**
- **By 2030, primary production, die-casting, and recycling are anticipated to contribute 68%, 24%, and 7%, respectively, to SF_6 emissions from magnesium production.**

Projected Trends

Aluminum Production

From 2015 through 2030, emissions from aluminum production are projected to double in the BAU scenario. Over the projection period, the analysis assumed that the effective emission factors (e.g., GWP-weighted emissions per production) will remain constant at 2015 values; consequently, future emissions will be driven by increasing aluminum production.

Country-specific production projections from 2020 through 2050 were estimated based on a global aluminum production compounded annual growth rate based on historical production data from 2005 through 2015.[67] Future growth rates in production in individual countries might be significantly different from the rest-of-world rate.

From 2015 through 2030, aluminum production is expected to grow at about 6% per year. The greatest growth in production is expected to occur in China, where annual aluminum production is projected to increase by about 45,000 metric tons by 2030.

Following the achievement of its previous target in 2006, the International Aluminium Institute (IAI) endorsed a new voluntary target in 2008 of reducing PFC emission intensity by at least 50% by 2020 as compared with the 2006 PFC emission intensity (equivalent to a reduction of 93% compared with 1990). China is not expected to participate in efforts to achieve this target,[68] but if other countries achieve this goal, future emissions could be lower than the projected emissions in the BAU scenario.

Magnesium Production

Emission projections for magnesium are based on estimates that, by 2020, the global production growth rate of magnesium metal will be 3% per year, on average, with the most rapid growth expected in the die-casting industry at 4% per year.[69] Die-casting growth is anticipated to be influenced by increasing investments by Western, Japanese, and Taiwanese companies in China to meet their respective domestic demand for cameras, computers, and automobile parts. New facility construction and facility capacity expansion

are anticipated to meet growing global demand for magnesium in applications such as automotive light-weighting to improve fuel economy. Hence, SF_6 emissions are projected to steadily increase, on average, by 3% annually from 2015 through 2030 in response to the anticipated growth in the industry.[70]

Historical Aluminum Production Emissions

Historical aluminum production emission reductions were partially offset by a doubling of global aluminum production between 1990 and 2010. Total PFC emissions began to increase from 2010 through 2015 as global aluminum production continued to increase, especially in China, and efforts to reduce emissions slowed. The IAI estimates of aluminum production in 2015 are similar to the production estimates in this analysis for 2015 (within 1%).[71] However, the IAI estimates lower emissions (about 30% less than the emission estimate for 2015 in this analysis) and may reflect more accurate information on the actual emissions from individual facilities using a particular electrolytic cell type.

Historical Magnesium Production Emissions

In the absence of emission control measures, the rapid growth of the magnesium manufacturing industry is expected to significantly increase future SF_6 emissions from magnesium production and processing. However, global efforts in recent years to eliminate the use of SF_6 in this application have reduced potential emission growth.

Specifically, in 2003, the EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry formed a global industry commitment through the International Magnesium Association (representing approximately 80% of magnesium production and processing outside of China) to eliminate SF_6 emissions from operations by the end of 2010.[72] The U.S. partnership has ended, but facilities in the United States that contain magnesium production processes are required to annually report emissions under subpart T of EPA's Greenhouse Gas Reporting Program (40 CFR Part 98). In addition, regulatory efforts in Europe and Japan and CDM projects in Brazil and Israel have resulted in significantly reduced emissions.

- ***Emissions from aluminum production decreased by 67% from 1990 through 2015, but emissions are estimated to double from 2015 through 2030, primarily because of increased production. Most of this growth is expected to occur in China, which is projected to produce more than two-thirds of the world's PFC emissions from aluminum production by 2030.***
- ***Magnesium production emissions decreased significantly from 1990 through 2015, but emissions are expected to increase because of growing global demand for magnesium in the technology and automotive sectors.***

Metals

Aluminum and Magnesium Production

Key Points

- **The metals source category emits 1% of the global baseline emissions in 2030, making this source a small emitter relative to the others.**
- **Aluminum production has the greatest mitigation potential at 22 $MtCO_2e$—four times the contribution from magnesium production.**
- **The abatement potential at cost-effective prices ($0/$tCO_2e$) is estimated to be 1% of the metals baseline in 2030, rising to 18% at prices below $20/$tCO_2e$.**

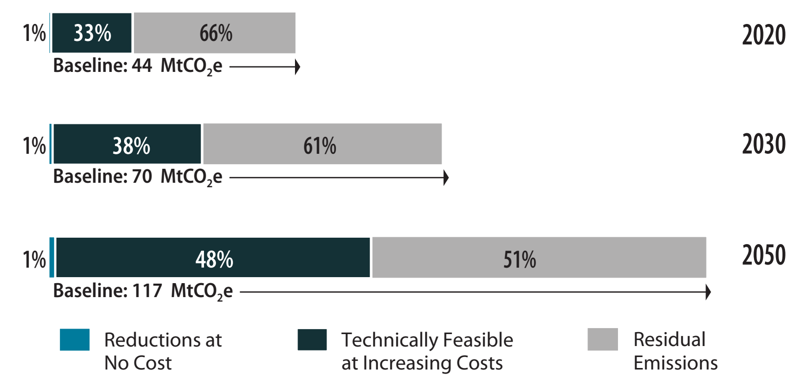
Abatement Measures

Abatement measures for metals come from aluminum and magnesium production. Abatement options considered in the primary aluminum production industry involve (1) a minor retrofit to upgrade the process computer control systems and (2) a major retrofit to the process computer control systems coupled with the installation of alumina point-feed systems. The analysis does not include the installation of alumina point-feed systems on its own because it would be very unlikely that an aluminum production facility would install alumina point-feed systems without also installing or upgrading process computer control systems.

For the production and processing of magnesium, replacing SF_6 with an alternative cover gas is the principal abatement measure. The three options for alternative cover gas in magnesium production are SO_2, HFC-134a, and Novec™ 612. Although toxicity, odor, and corrosive properties are a concern of using SO_2 as a cover gas, it can potentially eliminate SF_6 emissions entirely through improved containment and pollution control systems. HFC-134a, along with other fluorinated gas, contains fewer associated health, odor, and corrosive impacts than SO_2, but it does have a GWP. The replacement of SF_6 with Novec™ 612 is under evaluation and is currently being used in one remelt and die-casting facility in the United States. Each of the three cover gases has a reduction efficiency between 95% and 100%.

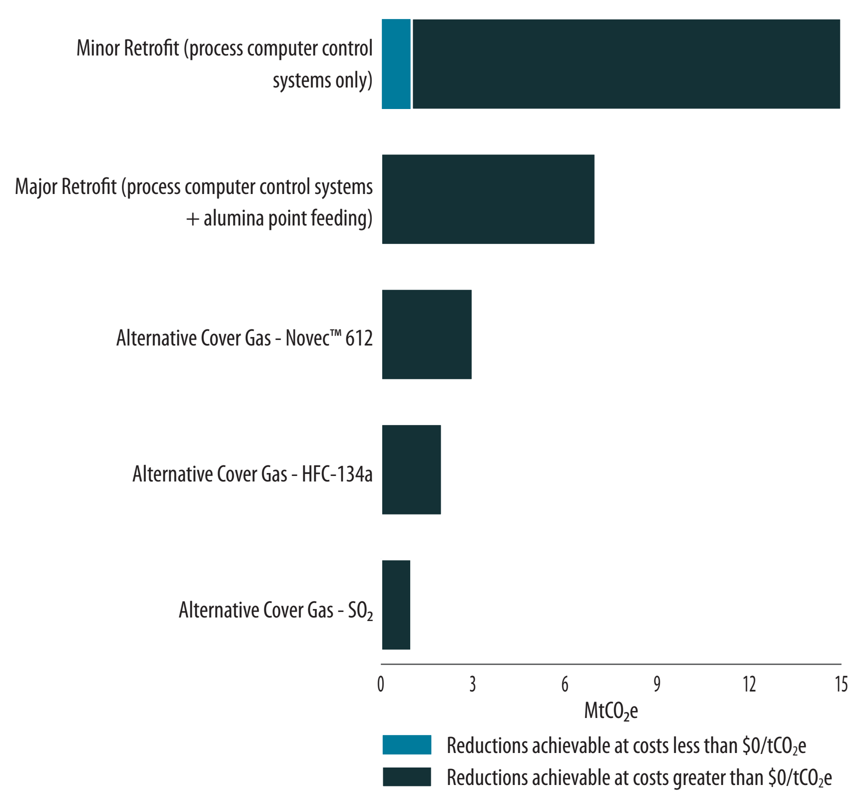
Total Reduction Potential

Reducing emissions by 1% compared with the 2020 baseline is cost-effective. An additional 33% reduction is available using technologies with increasingly higher costs. The emission reduction potential at increasing costs rises to 38% in 2030 and to 48% in 2050.



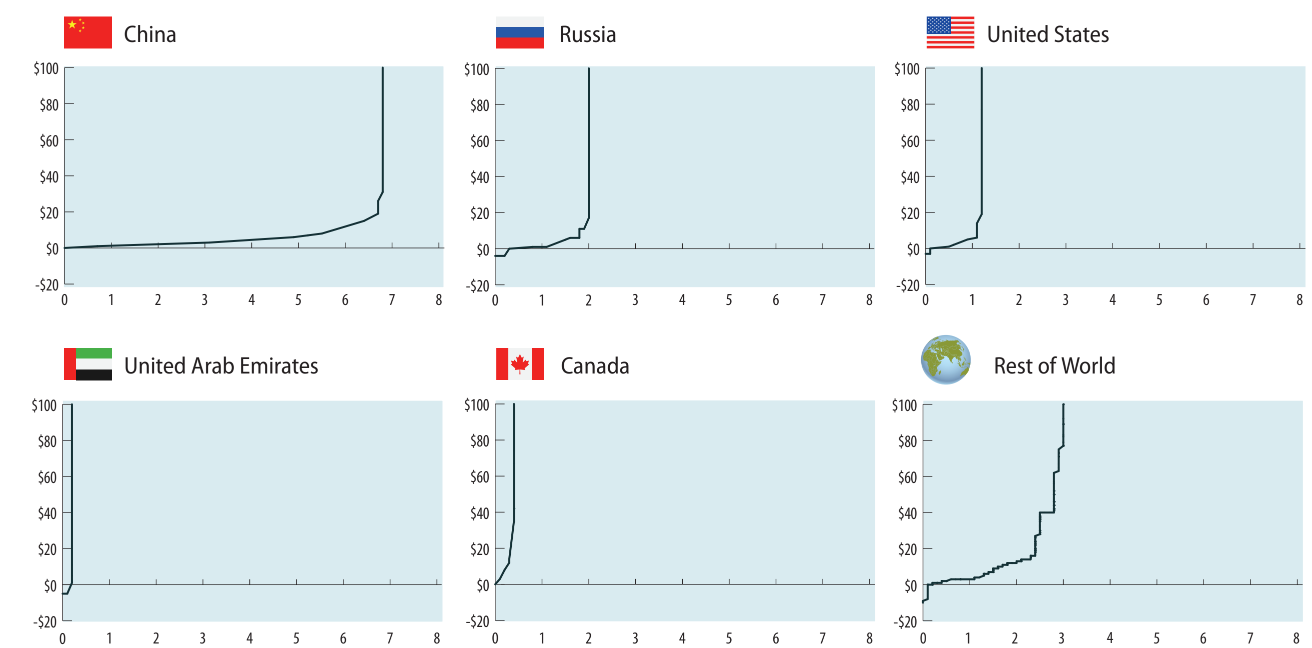
Reduction Potential by Technology

In 2030, minor retrofitting of process computer control systems is the leading emission abatement measure in metals manufacturing, and 0.5 $MtCO_2e$ of reductions are achievable at prices below $0/$tCO_2e$. At prices greater than $0/$tCO_2e$, this measure can mitigate 14 $MtCO_2e$.



Marginal Abatement Cost Curves, 2030

China has the highest baseline emissions for the metals source category in 2030, followed by Russia, the United States, the United Arab Emirates, and Canada. China contributes to 60% of global abatement potential, and the top 5 emitters combined contribute to 83% of global abatement potential.



Abatement Potential

Metals production's abatement potential is estimated to be approximately 28 $MtCO_2e$ in 2030, or 39% of the source's baseline emissions. Break-even prices as low as $20/$tCO_2e$ can achieve nearly half of the metals production's mitigation potential, and a price of $5/$tCO_2e$ can mitigate a quarter of metals emissions.

Reduction technologies used in the production of aluminum offer the highest global abatement potential in the metals source category. Minor and major retrofit upgrades can potentially mitigate 21 $MtCO_2e$ in 2030, or 34% of aluminum's baseline emissions. In contrast, using SO_2, HFC-134a, and Novec™ 612 as alternative cover gases for magnesium production can mitigate 6 $MtCO_2e$, or 98% of magnesium's baseline emissions. These alternative gases have low or zero GWP, which leads to high reduction efficiency and potential abatement.

China, Russia, and the United States are the top 3 countries with the highest abatement potential in 2030. China has the potential to mitigate 17 $MtCO_2e$, approximately a quarter of metal emissions. Russia and the United States have the potential to mitigate 3 $MtCO_2e$ and 2 $MtCO_2e$, respectively. Although these nations have much lower potential than China, Russia, and the United States can achieve higher abatement potential at lower break-even prices. For example, 61% and 73%, respectively, of their national abatement potential is possible at break-even prices less than $20/$tCO_2e$; whereas China can reach 40% of its potential at the same prices.

Substitutes for Ozone-Depleting Substances

Source Background

HFCs are used as alternatives to several classes of ODSs that are being phased out under the terms of the Montreal Protocol. ODSs, which include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and HCFCs, have been used in a variety of industrial applications, including refrigeration and air-conditioning equipment (ref/AC), aerosols, solvent cleaning, fire extinguishing, foam production, and sterilization. HFCs are not harmful to the stratospheric ozone layer, but they are powerful GHGs. Calculations of HFC emissions from the use of substitutes for ODSs are modeled by end use and country.[73] End uses are expected to transition from ODSs to HFCs in response to the ODS phase-out.

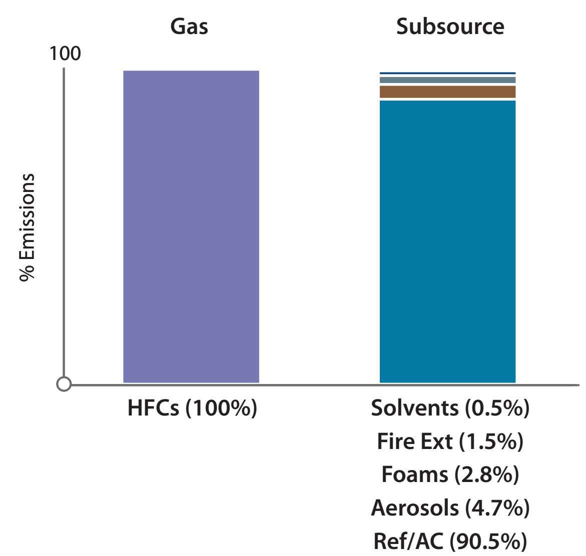
HFCs are first consumed during manufacture and are mostly emitted to the atmosphere over the lifetime of the equipment or product from equipment leaks, servicing, and disposal. The EPA used a modeling approach to determine emissions from the various ODS end-use sectors that have transitioned to HFCs.

Historical Trends

Global ODS substitute emissions were estimated to rise from 0.01 $MtCO_2e$ to 705 $MtCO_2e$ between 1990 and 2015, driven by growth primarily in ref/AC. The growth in emissions up to 2005 is primarily driven by the transition to HFCs under the Montreal Protocol in OECD countries. This trend was accelerated from 2005 through 2015 as emissions of ODS substitutes from non-OECD countries played an increasingly important role.

2030 Emissions by Gas and Subsource

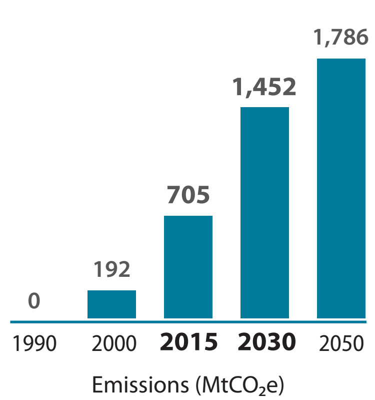
HFCs are the primary alternative to ODSs. PFCs and hydrofluoroethers (HFEs) are also used as alternatives but to a substantially lesser extent than HFCs; therefore, emissions from these gases are not estimated in this report. The ref/AC subsource is the most significant contributor to HFC emissions in 2030, comprising approximately 90% of emissions.



Projected Emissions & Top Emitting Countries

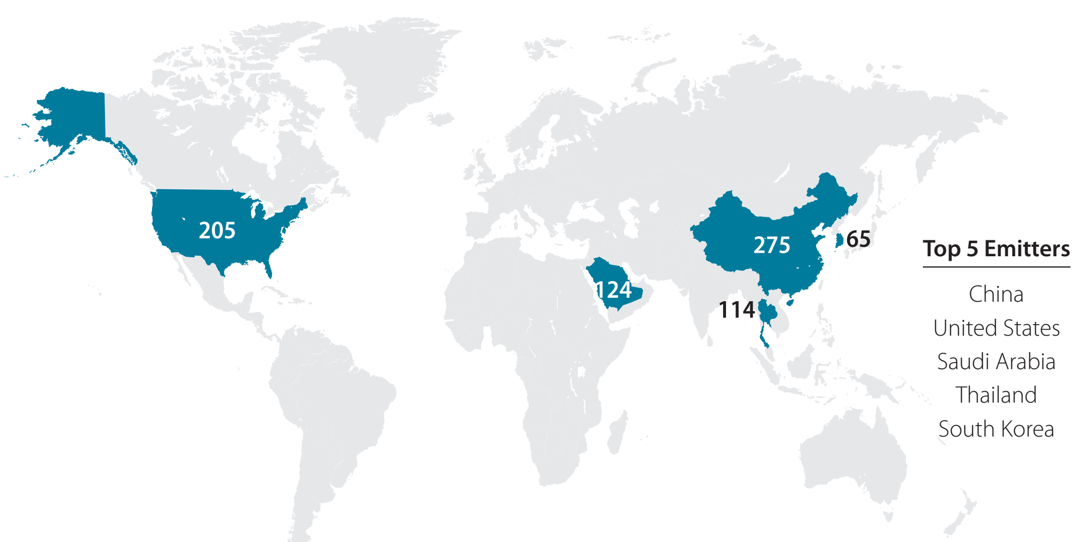
Emissions ($MtCO_2e$)

From 2015 through 2030, HFC emissions from use as substitutes for ODS are projected to double.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 669 $MtCO_2e$



Key Points

- **Global HFC emissions are expected to increase significantly through 2030 because of the continued transition to ODS substitutes.**
- **Growth of ref/AC in developing countries is the primary driver of the significant increase in HFC emissions through 2030, particularly in China, Saudi Arabia, and Thailand. Growing populations, economic development, and a lack of HFC alternatives in these countries are driving the increasing demand for HFC use in ref/AC.**

Projected Trends

Through 2030, emissions and consumption of HFCs are expected to grow in both developed and developing countries but will grow much more quickly in developing countries. In contrast to developing countries where emission increases are driven by growth in the amount of equipment used, emission increases in developed countries are driven primarily by the aging and replacement of existing ODS equipment. Reduction in consumption through enhanced recovery and reuse, transitions to more efficient equipment, and the use of low- or no-GWP alternatives could avert these projected emission increases.

For this analysis, the BAU scenario does not incorporate measures to reduce or eliminate the future emissions of these gases, other than those regulated by law or otherwise largely practiced in the current market, including in the European Union, Australia, and Japan. These developed country–level agreements control HFC consumption and have led to reduced emission growth. Reduction schedules from these policies were applied across all sectors and, for the European Union, across all countries.

Although the BAU forecast incorporates some transitions that are occurring currently (e.g., HFO-1234yf replacing HFC-134a in light duty vehicle air-conditioning in some OECD countries),[74] the model does not project all future market transitions, including those anticipated by industry. There is significant uncertainty as to what chemicals will replace HFCs in applications using ODS substitutes, particularly in developing countries. Although existing policies in the European Union, Australia, and Japan were modeled as mentioned above, future policies that could affect consumption of HFCs, and therefore emissions, were not modeled here.[75] For instance, over 70 countries have ratified the Kigali Amendment to the Montreal Protocol, which calls for a phase-down in HFC consumption. The BAU forecasts for those countries do not attempt to explicitly model any specific actions taken to comply with the Kigali Amendment because the actions that would be taken are unknown at this time and would be decided at the national level.

Key Points

- The global abatement potential for the ODS substitutes source category reaches 549 $MtCO_2e$—roughly 38% of baseline emissions—in 2030.
- HFC emissions from ref/AC manufacturing make up the greatest mitigation potential from ODS substitute sources, reaching 515 $MtCO_2e$, or 35% of baseline emissions in 2030.
- Aerosols have the second highest abatement potential, reaching 33 $MtCO_2e$.
- Fire suppressants, solvents use, and foams represent just 0.6% of mitigation potential.

Substitutes for Ozone-Depleting Substances

Abatement Measures

The ODS substitutes source category contains five sources and their subsequent abatement measures: aerosols; solvents; fire protection; foams manufacturing, use, and disposal; and ref/AC.

Aerosol abatement measures fall into two categories: consumer products and pharmaceutical products. Abatement measures for consumer aerosols include transitioning to a replacement propellant and converting to a not-in-kind alternative such as a finger pump. For pharmaceutical products, this analysis considers the use of dry powder inhalers.

Measures to abate emissions from the use of solvents include precision or electronic cleaning on retrofitted and nonretrofitted equipment. The nonretrofitted options account for greater emissions coming from developing countries performing the same cleaning processes as developed nations but with fewer emission control technologies.

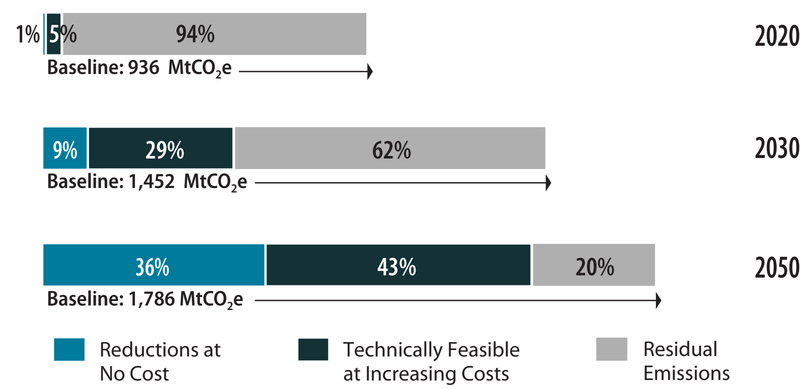
For fire protection, this analysis considers options that use zero-GWP or low-GWP extinguishing agents. The options are applied to technologies that protect against Class A surface fire hazards or Class B fuel hazards in large (>3,000 m³) marine applications.

The abatement measures considered for foam manufacturing fall into the categories of replacing HFCs with low-GWP blowing agents or properly recovering and disposing of foam contained in equipment.

The refrigeration and air-conditioning discussion considers 20 new technologies and three improved technician practices that are applicable in either a residential, retail, or transportation setting.

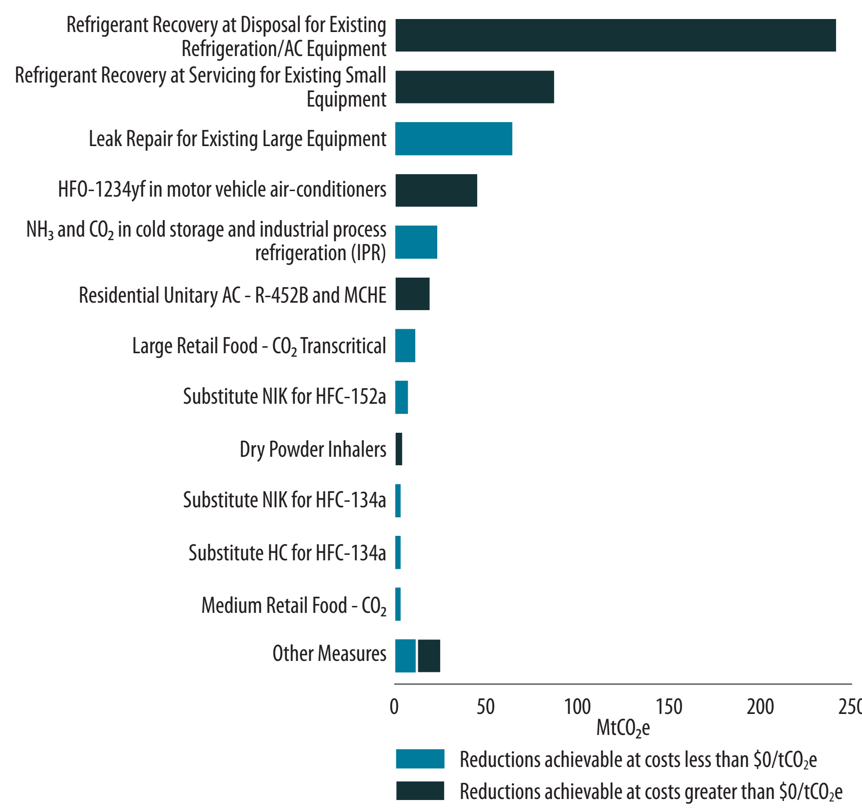
Total Reduction Potential

Reducing emissions by 1% compared with the 2020 baseline is cost-effective. An additional 5% reduction is available using technologies with increasingly higher costs. The cost-effective reduction potential rises to 9% in 2030 and to 36% in 2050.



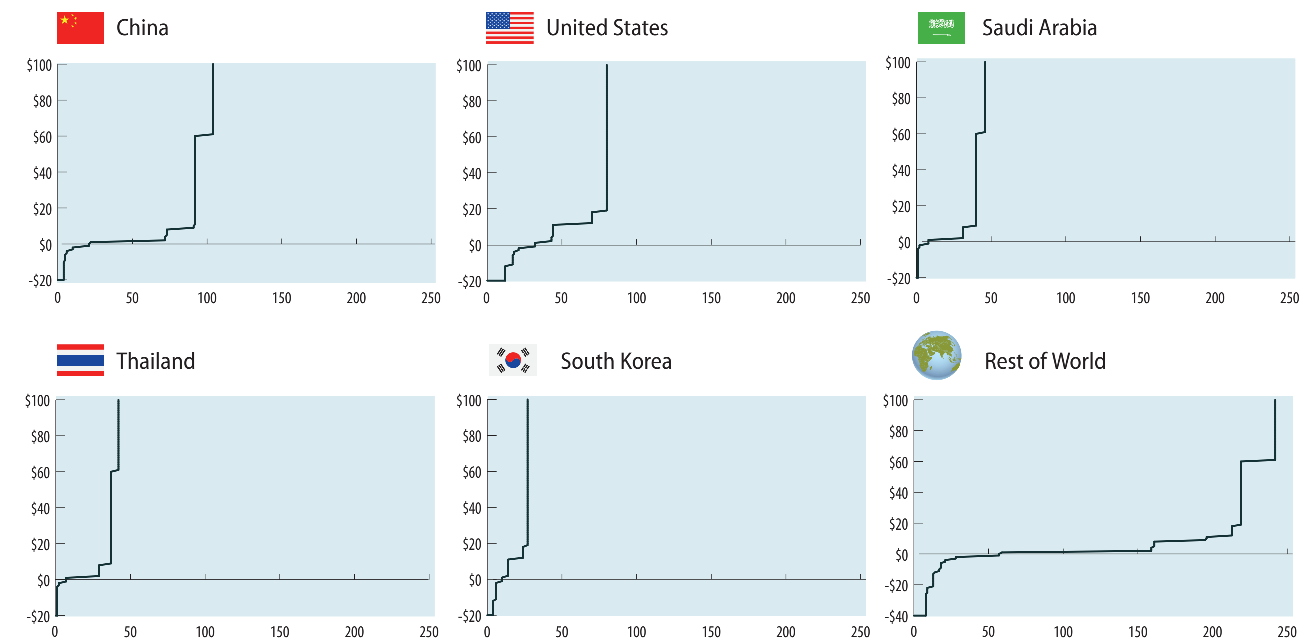
Reduction Potential by Technology

In 2030, the top 2 abatement measures come from the refrigeration and air-conditioning subsource. Refrigerant recovery at disposal for existing refrigeration/AC equipment is the leading measure with 242 $MtCO_2e$ of potential abatement at prices above $0/$tCO_2e$. Refrigerant recovery at servicing for existing small equipment is the second leading measure with 88 $MtCO_2e$ of potential abatement at prices above $0/$tCO_2e$.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of baseline emissions represent 55% of global abatement potential in the source category in 2030. China has the highest emissions and can potentially abate 106 $MtCO_2e$. The United States has the second largest potential abatement in 2030, reaching 81 $MtCO_2e$.



Abatement Potential

Abatement of HFC emissions from this collection of sources is challenging given the available technology. This analysis estimates that available abatement technologies can only abate approximately 1% of emissions from fire protection and foam-related emissions. Abatement potential in emissions from solvent use rises to 9%. Abatement potential in emissions from aerosols is 48% of aerosol-related emissions because of readily available ways to remove aerosols from consumer products.

Emissions from ref/AC contribute to 90% of baseline emissions from the ODS substitutes category and are also the largest source of potential abatement. Abatement measures targeting ref/AC emissions have the potential to abate 515 $MtCO_2e$ of emissions, which represents 39% of baseline ref/AC emissions.

Even though most individual abatement technologies in this category have relatively low expected effectiveness, as a whole substantial emission reductions are available at cost-effective prices. Across all ODS substitute sources, 25% of abatement potential is available at prices below $0/$tCO_2e$. By contrast, out of the total non-CO_2 emission abatement potential across all sources globally, only 21% is available at prices below $0/$tCO_2e$.

Just 3 of the 42 technologies considered across all ODS sources provide 72% of abatement potential. The largest amount of potential abatement can be achieved through recovering refrigerant at disposal for existing ref/AC equipment (242 $MtCO_2e$) at prices above $0/$tCO_2e$; recovering refrigerant at servicing for existing small equipment unlocks an additional 88 $MtCO_2e$ at costs above $0/$tCO_2e$. Finally, 65 $MtCO_2e$ is achievable below prices of $0/$tCO_2e$ by repairing leaks in existing large equipment.

In 2030, China, the United States, and Saudi Arabia have the highest emissions from the ODS substitutes source category, making them the largest potential sources of abatement as well. China represents 106 $MtCO_2e$ of abatement potential, followed by 81 $MtCO_2e$ from the United States. The top 3 emitters combined account for 43% of the global abatement potential.

HCFC-22 Production

Source Background

Trifluoromethane (HFC-23) is generated and emitted as a by-product during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used primarily as a feedstock for production of synthetic polymers and in emissive applications, primarily ref/AC. Because HCFC-22 depletes stratospheric ozone, its production for nonfeedstock uses is scheduled to be phased out under the Montreal Protocol. However, HCFC-22 production for feedstock uses is permitted to continue indefinitely. HFC-23 emissions from HCFC-22 production can be avoided through thermal destruction and reduced through process optimization.

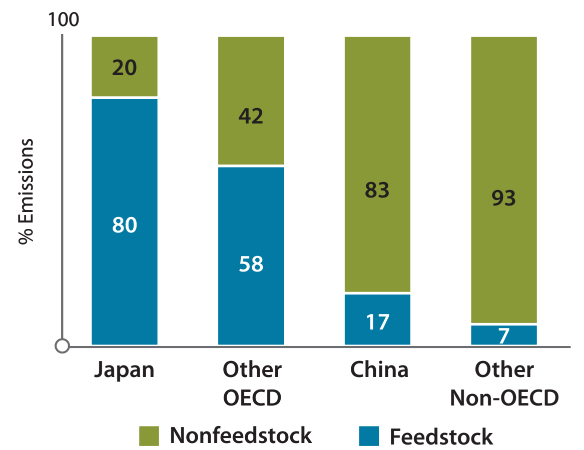
Historical Trends

Global HFC-23 emissions from HCFC-22 production are estimated to have increased by 12% between 1990 and 2015, driven by high growth in global HCFC-22 production during that period.

Between 1990 and 2005, the majority of emissions shifted from OECD countries to non-OECD Asia. This shift is due to both a combination of increased use of emission controls and the phase-down of HCFC-22 under the Montreal Protocol in OECD countries, as well as increased HCFC-22 production in China and India.

2030 Emissions by Region and End Use

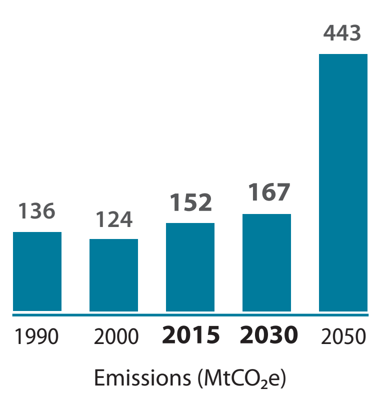
In 2030, HCFC-22 production for emissive (i.e., nonfeedstock) purposes is expected to be phased out in developing countries because of the requirements of the Montreal Protocol. HCFC-22 production for feedstock use is anticipated to grow at 5% per year globally. Before the phaseout of production of HCFC-22 for emissive purposes under the Montreal Protocol, feedstock production made up 80% of HCFC-22 production in Japan, 58% in other OECD countries, 17% in China, and 7% in all other non-OECD countries. From 2030 onward, HCFC-22 production is solely for feedstock use.



Projected Emissions & Top Emitting Countries

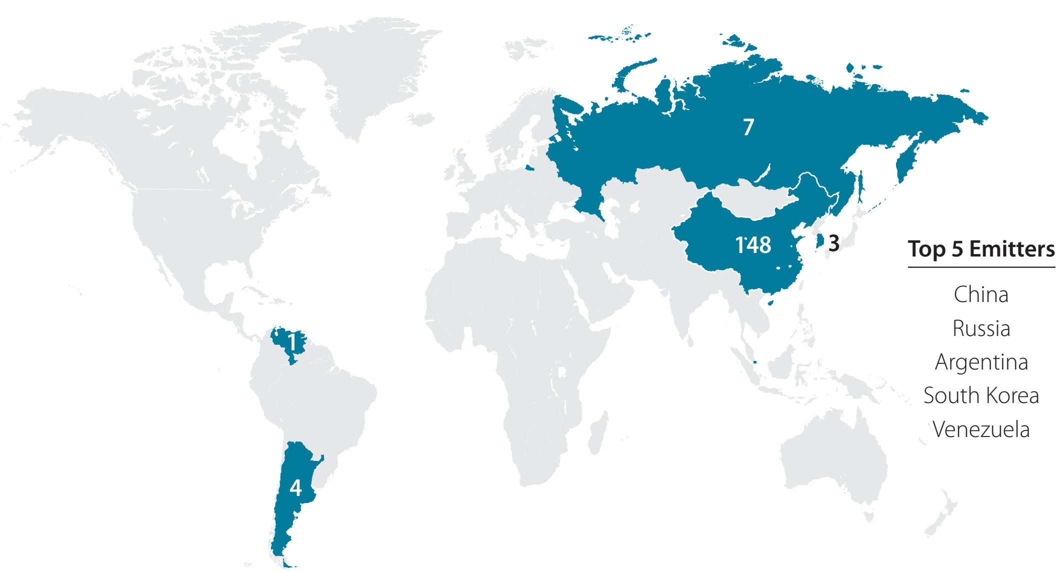
Emissions ($MtCO_2e$)

From 2015 through 2030, HFC-23 emissions from HCFC-22 production are projected to increase by 10%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 3 $MtCO_2e$



Top 5 Emitters

China
Russia
Argentina
South Korea
Venezuela

Key Points

- Global HFC-23 emissions from HCFC-22 production are expected to decrease between 2015 and 2020 but then increase through 2030 because of the continued demand for HCFC-22 for feedstock uses.
- Nonfeedstock HCFC-22 production will be phased out in developed countries between 2015 and 2020 and in developing countries between 2015 and 2030.
- Developing countries, particularly China and India, are driving the significant increase in HFC-23 emissions through 2030.

Projected Trends

Global HFC-23 emissions from HCFC-22 production are expected to decrease between 2015 and 2020, increase slightly through 2030, and then increase significantly through 2050. Key factors influencing the trend in the global BAU emission scenario from 2015 through 2030 include a phase-out of nonfeedstock HCFC-22 production in developed countries between 2015 and 2020, which results in a temporary reduction in HFC-23 emissions over that period, and a phase-out of nonfeedstock HCFC-22 production in developing countries between 2015 and 2030. HCFC-22 production for feedstock use is expected to grow at approximately 5% per year.

HFC-23 emissions are also expected to begin increasing after 2020 through 2030 and beyond because some facilities with CDM projects (mitigation projects funded by developed countries under the Kyoto Protocol) are no longer expected to be destroying HFC-23 emissions. Destruction of HFC-23 from HCFC-22 production was previously a major source of credits in the CDM program. Some facilities with CDM projects are no longer destroying HFC-23 emissions; however, China recently constructed new destruction facilities on 15 HCFC-22 production lines, although this is not explicitly modeled in the BAU.[76]

Future emission and abatement levels are particularly uncertain. Future policies (e.g., under the Montreal Protocol) are not included in the BAU emission projections and could affect total production of HCFC-22 and therefore emissions of HFC-23. For example, the Kigali Amendment to the Montreal Protocol mandates all HCFC-22 producing facilities to collect and destroy HFC-23 by-product beginning in 2020 to the extent practicable. Since most, if not all, HCFC-22 production plants have access to existing destruction facilities, they could restart the equipment that was used to previously destroy HFC-23 if the equipment is not currently in use. Changing emission rates as a result of implementing abatement technology, process optimization, or other means may also have a significant impact on emissions. These factors taken together suggest that a significant portion of projected emissions can be avoided.

HCFC-22 Production

Key Points

- **The global abatement potential for the HCFC-22 production source category is 147 $MtCO_2e$ (88% of baseline emissions) in 2030.**
- **China, Argentina, and South Korea represent 96% of the maximum abatement potential in 2030.**
- **Thermal oxidation is the only abatement option considered for the HCFC-22 production source category.**
- **Abating HCFC-22 emissions is relatively low cost: all potential abatement is achievable at costs below $5/$tCO_2e$.**

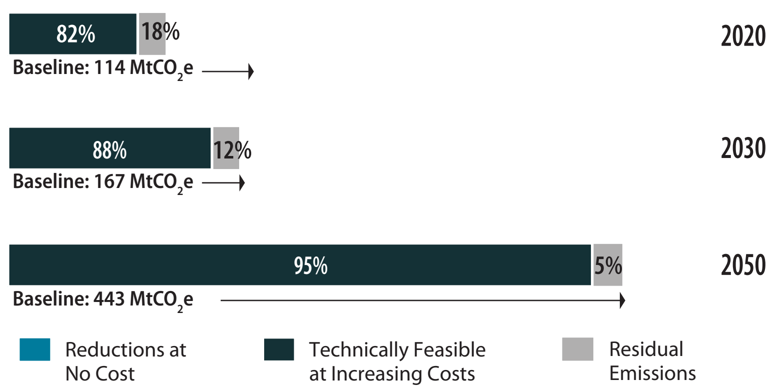
Abatement Measures

For the HCFC-22 production source category, this analysis assumed that facilities in most developed countries have already adopted abatement measures. As a result, abatement potential is limited to developing countries. This analysis examined only one abatement measure—thermal oxidation. This measure destroys halogenated organic compounds by oxidizing HFC-23 to hydrogen fluoride, water, and CO_2. The fraction of production time that the device is running determines the actual reduction potential. The unit may require downtime because destruction requires high temperatures and hydrogen fluoride is highly corrosive. This analysis assumed a reduction efficiency of 95%, indicating that this technology can abate 95% of emissions when used. Furthermore, the HCFC-22 production source category has a 95% technical effectiveness in this analysis, meaning that this measure has the potential to reduce 95% of baseline emissions at the national level.

Thermal oxidation equipment has a lifetime of approximately 20 years, making it a long-term capital investment. Installing thermal oxidation in a new plant is cheaper than in a preexisting plant. The estimated capital cost to upgrade an existing plant is approximately $5.2 million, but only $4 million to build this technology into a new plant while the plant is under construction. Another option is to restart a preexisting incinerator, which costs $400,000, on average. Furthermore, the annual operating and maintenance cost is approximately $200,000. Thermal oxidation does not provide any revenue or cost savings.

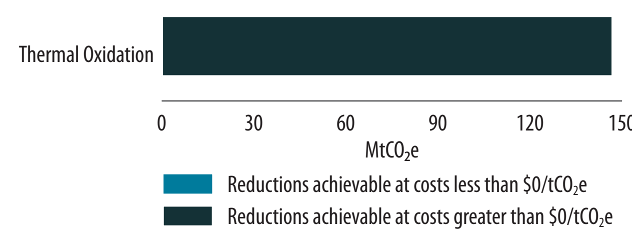
Total Reduction Potential

There are no emission reductions available in HCFC-22 production at prices below $0/$tCO_2e$. However, in 2020, an 82% reduction is achievable when using technologies with increasingly higher costs, and this percentage rises to 88% in 2030 and to 95% in 2050.



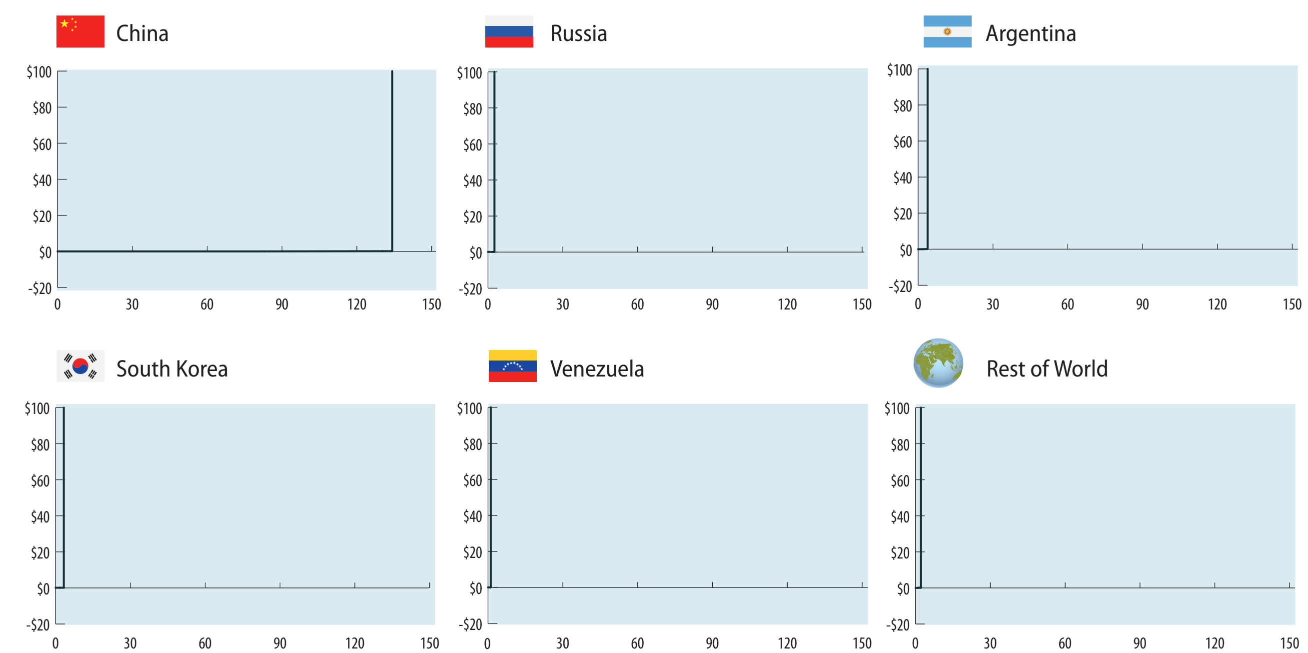
Reduction Potential by Technology

Thermal oxidation was the only abatement measure modeled for the HCFC-22 production source category. The technology has the potential to abate 147 $MtCO_2e$ in 2030. All the reductions are achievable at costs greater than $0/$tCO_2e$.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of baseline emissions represent 98% of all potential global abatement in the source category in 2030. China is the highest emitting country but also contributes to 91% of global abatement potential for the source category, or 134 $MtCO_2e$, in 2030. The MAC curves in this source category look like straight lines because only one abatement technology was modeled, leading most abatement to fall at very similar price points.



Abatement Potential

The global abatement potential for the HCFC-22 production source category is estimated to rise over time. In 2020, the maximum abatement potential is 93 $MtCO_2e$, or 82% of baseline emissions. However, abatement potential is expected to increase to 147 $MtCO_2e$ and 420 $MtCO_2e$ in 2030 and 2050, respectively, or approximately 88% and 95% of baseline emissions. Maximum abatement potential can be achieved at little or no cost; all of the potential can be reached with break-even prices between $0/$tCO_2e$ and $1/$tCO_2e$.

China has the leading abatement potential from the HCFC-22 production source category across the modeled time horizon. In 2030, China's abatement potential is 130 $MtCO_2e$ higher than the country with the second highest potential, Argentina. Furthermore, China experiences growth in its mitigation potential over time. In 2015, China can abate 43 $MtCO_2e$, or 38% of baseline emissions. However, by 2030, the country is estimated to mitigate 134 $MtCO_2e$, which is the equivalent of 80% of the baseline emissions and 85% of the source category's total annual abatement potential.

In 2030, the other leading countries with the most abatement potential are Argentina, South Korea, Russia, and Venezuela. These countries can abate 7% of the baseline emissions and contribute to 7% of the potential mitigation from the HCFC-22 production source category. Argentina and Venezuela can potentially abate 4 $MtCO_2e$ and 1 $MtCO_2e$, while Russia and South Korea can each potentially reach 3 $MtCO_2e$ in abatement.

AGRICULTURE

Introduction

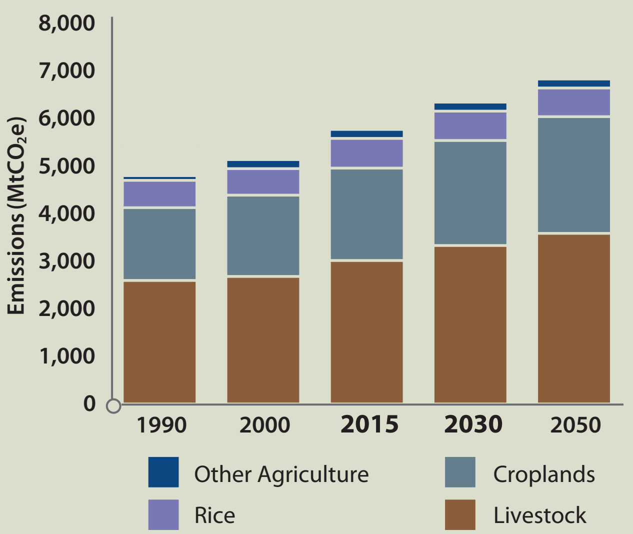
The agriculture sector is the largest contributing sector to global emissions of non-CO_2 GHGs, accounting for 48% of emissions in 2015. This section presents global agriculture-sector CH_4 and N_2O historical and projected emissions and the mitigation potential from the following source categories:

- Livestock (CH_4, N_2O)
- Croplands (CH_4, N_2O)
- Rice cultivation (CH_4, N_2O)

Projections and MAC curves were estimated for all source categories; however, within croplands, the mitigation analysis was restricted to major crops that represent 61% of global croplands. Also, rice is considered separately.

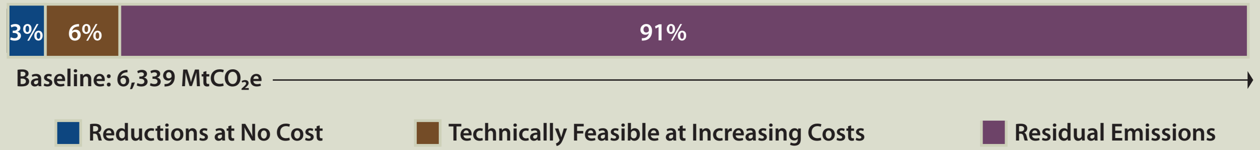
Between 2015 and 2030, global agriculture-sector emissions are projected to increase 10%, reaching 6,339 $MtCO_2e$ in 2030. Agricultural soil emissions and enteric fermentation emissions are projected to increase the largest amount, by 14% and 12% between 2015 and 2030, respectively. Emissions in the agriculture sector are projected to increase because of increased fertilizer consumption, crop production, and livestock populations, which are driven by demand for animal products. The growth rate in the demand for animal products is expected to increase significantly in developing economies but is expected to be slower or negative in non-Annex I economies.

Historical and Projected Emissions from the Agriculture Sector



Mitigation potential from the agriculture sector is estimated to be approximately 593 $MtCO_2e$ in 2030. This mitigation potential is 9%, 3%, and 36% of livestock, croplands, and rice cultivation emissions, respectively; 9% of overall agriculture-sector emissions; and 16% of total global non-CO_2 mitigation potential in that year.

Emission Reduction Potential, 2030



Livestock

Enteric Fermentation and Manure Management

Source Background

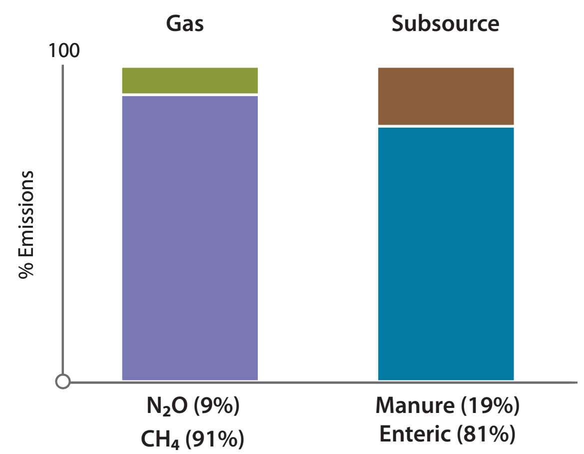
Emissions from livestock include enteric fermentation and manure management. Enteric fermentation is a normal mammalian digestive process, where gut microbes produce CH_4 that the animal exhales. Livestock manure management produces CH_4 emissions during the anaerobic decomposition of manure and N_2O emissions during the nitrification and denitrification of the organic nitrogen content in livestock manure and urine.

Historical Trends

Between 1990 and 2015, combined CH_4 and N_2O emissions from livestock increased 16%. Roughly 80% of livestock emissions are CH_4 emissions from enteric fermentation. Between 1990 and 2015, global CH_4 emissions from enteric fermentation and manure management increased by 13% and 33%, respectively. The total cattle population increased by 31%, and livestock production systems shifted from grazing and mixed systems toward intensive specialized livestock production systems that typically have manure management systems with high CH_4 emissions.[77,78] The primary driver for the increase in emissions from both livestock sources was the increase in livestock populations, most of which occurred in Asia, Africa, and the Middle East. In contrast, emissions in developed economies experienced more stagnant and even negative growth.

2030 Emissions by Gas and Subsource

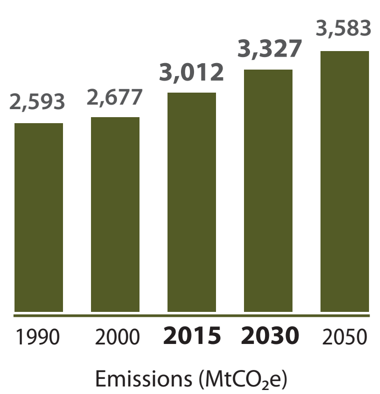
The vast majority of emissions from livestock are CH_4 emissions from enteric fermentation.



Projected Emissions & Top Emitting Countries

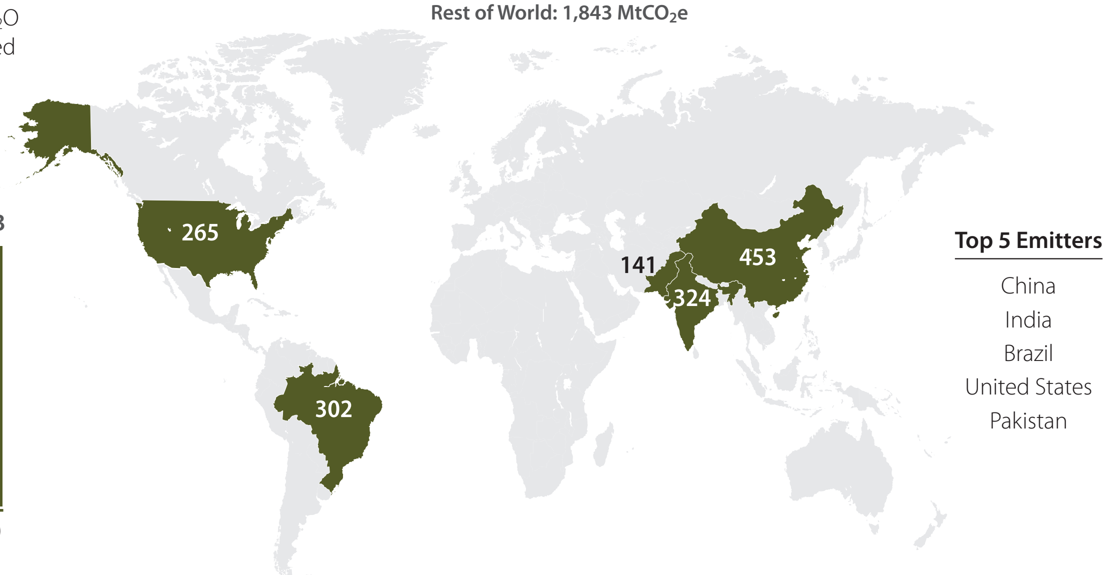
Emissions (MtCO$_2$e)

From 2015 through 2030, CH_4 and N_2O emissions from livestock are projected to increase by approximately 10%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 1,843 MtCO$_2$e

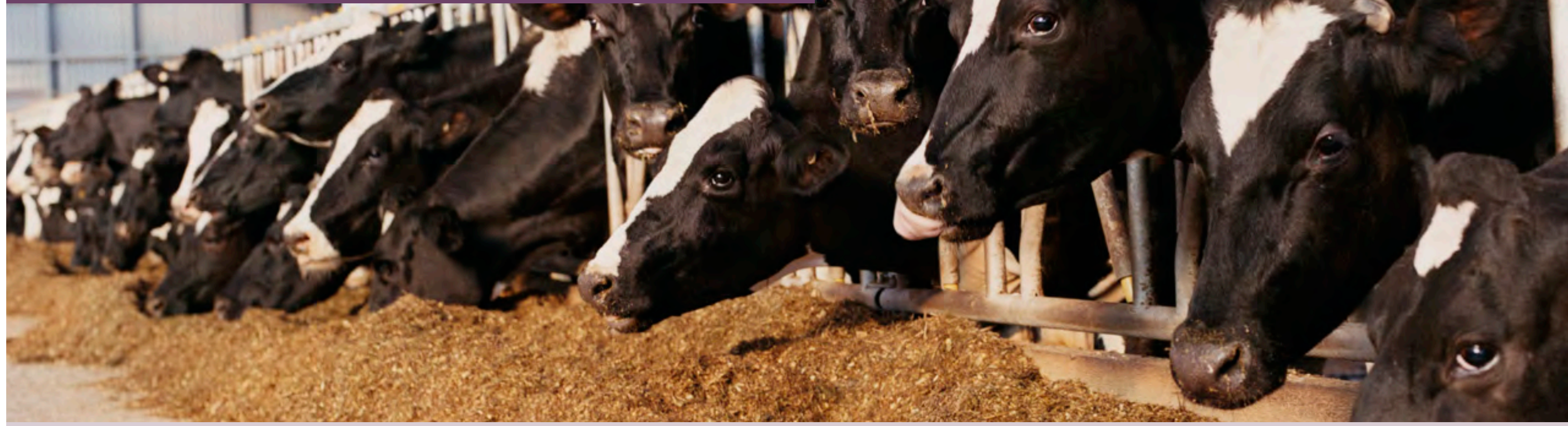


Top 5 Emitters

China
India
Brazil
United States
Pakistan

Key Points

- **Livestock emissions are projected to increase by 10% between 2015 and 2030, with significant growth in emissions from enteric fermentation (+12%), and slower growth in emissions from manure management (+5%).**
- **Livestock populations, which are driven by demand for animal products such as meat and milk, dominate emission projections. Developing countries are expected to increase their livestock populations.**
- **Emissions from manure management are expected to be mitigated partly by an increased transition to less emissive manure management systems in developed economies.**



Projected Trends

From 2015 through 2030, emissions from enteric fermentation and manure management are projected to increase 12% and 5%, respectively. These projections assume increases in livestock populations, including 12% for dairy cows and cattle and 10% for poultry. However, these projections do not account for possible changes in emissions per head of livestock due to changes in management practices, animal feed, or genetics, all of which can increase or decrease emission estimates. For example, conversion to intensive specialized livestock production systems typically results in manure management systems with higher CH_4 emissions. Thus, these emission estimates may either over- or understate future emissions. The individual country-reported data may account for some of these practices.

Most enteric fermentation emissions come from dairy cows, cattle, and buffalo. World projections through 2025 show increases in meat product consumption, production, and trade, most of which is projected to occur in developing countries.[79] In China, demand and production of both meat and milk have been growing rapidly, and China is expected to be one of the largest sources of emissions from enteric fermentation through 2030. Total enteric emissions are projected to grow at a slower pace than the corresponding cattle population increase. In contrast, in developed countries, emissions from enteric fermentation are expected to decline through 2030. Cattle inventories are projected to decrease in the European Union and Russia because of increases in cattle productivity and decreases in animal product consumption.[80]

Manure management emissions are also projected to increase because of increasing populations of dairy cows, cattle, buffalo, and poultry, most of which are projected to occur in developing countries. Poultry production is projected to increase approximately 14% over the next decade, making it the primary driver of growth in global meat production.[81] 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. The increase in dairy cow and cattle populations over the next decade is projected to occur mostly in developing countries, which have lower per-animal manure management emission rates than developed countries. However, as dairy- and cattle-producing countries transform to larger livestock and manure management systems, the trend will likely be toward increasing CH_4 emissions.

Livestock

Enteric Fermentation and Manure Management

Key Points

- Livestock accounts for 24% of baseline non-CO_2 emissions in 2030.
- The largest low-cost reductions in emissions result from implementing strategies to improve feed conversion efficiency, incorporate feed supplements, and increase the use of small-scale anaerobic digesters.
- The abatement potential from livestock is 298 $MtCO_2e$ in 2030, or 9% of baseline emissions.

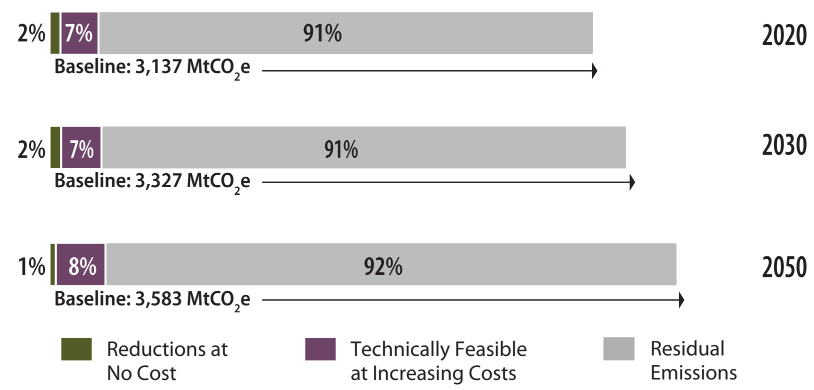
Abatement Measures

The analysis considers six enteric fermentation CH_4 abatement measures: improved feed conversion efficiency, antibiotics, bovine somatotropin (bST), propionate precursors, antimethanogen vaccines, and intensive grazing. Many of the currently available enteric fermentation abatement options work indirectly by increasing animal growth rates and reducing time to finish (or increasing milk production for dairy cows). These abatement measures achieve emission reductions because increased productivity means fewer animals are required to produce the same amount of meat or milk. Furthermore, several of the abatement measures are inexpensive to implement and are cost-effective at reducing emissions. For example, the average annual operation and maintenance cost for antibiotics ranges from \$4 to \$9 per head. Likewise, intensive grazing can save farmers up to \$180 annually while reducing emissions by 9 $MtCO_2e$ at break-even prices below \$0/tCO_2e.

In the case of manure management (CH_4 and N_2O), this analysis considers four large-scale abatement measures that are applied in developed regions: complete-mix, plug-flow, fixed-film digesters, and covered lagoons. Small-scale dome digesters are also included to provide a lower cost abatement measure and exhibit a measure used in developing regions. These digesters mitigate emissions from manure but also generate revenue for farms by generating heat and electricity from captured CH_4 gases. For example, implementing a complete-mix digester with an engine on a dairy cattle farm can create \$65 in energy revenue per head.

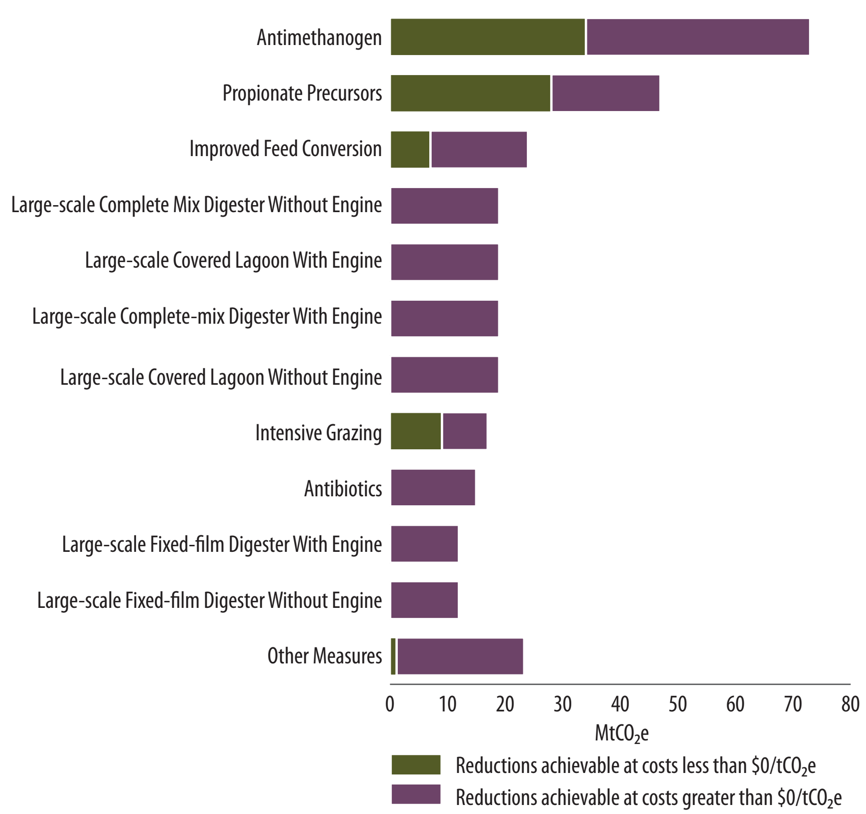
Total Reduction Potential

Reducing emissions by 2% compared with the baseline in 2020 is cost-effective. With increasingly higher costs, an additional 7% reduction is possible. The cost-effective reduction potential remains at 2% in 2030 and declines to 1% in 2050.



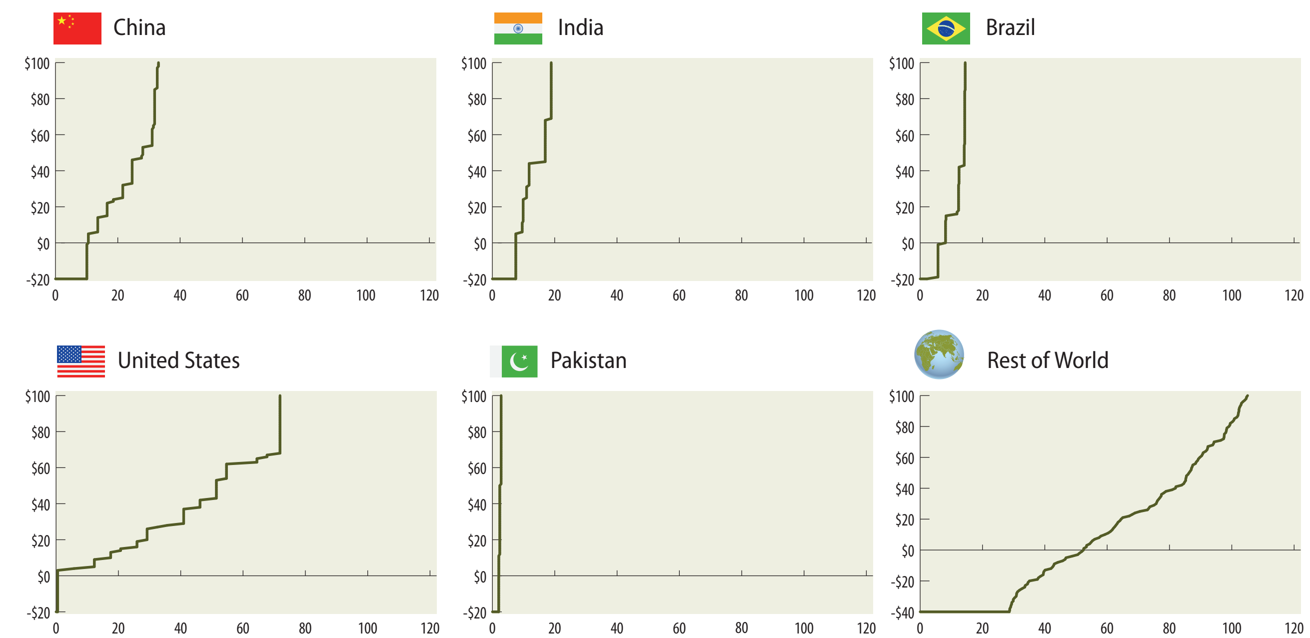
Reduction Potential by Technology

In 2030, antimethanogens offers the most overall potential abatement, followed by propionate precursors. Cost-effective abatement from antimethanogens, propionate precursors, and intensive grazing can reduce emissions by 70 $MtCO_2e$.



Marginal Abatement Cost Curves, 2030

China has the highest baseline emissions from livestock in 2030, followed by India, Brazil, the United States, and Pakistan. In total, the top 5 emitters represent 45% of baseline emissions. With the exception of the United States and India, abatement potential is less than 9% of the national baseline emissions for the top emitters.



Abatement Potential

Technologically feasible global abatement potential from livestock is estimated at 298 $MtCO_2e$ in 2030, a 9% reduction compared with the baseline. The total abatement potential is expected to remain roughly the same as a percentage of baseline emissions through 2050. In 2030, 26% of emission reductions are achievable at break-even prices below \$0.

Using antimethanogen has the highest global abatement potential in 2030, reaching 73 $MtCO_2e$, with propionate precursors as a close second, abating 47 $MtCO_2e$. Large-scale complete-mix digesters, covered lagoons with and without engines, and fixed-film digesters with engines all provide the third highest abatement potential at 19 $MtCO_2e$ each. Only five of the measures have abatement potential at no cost: antimethanogen, propionate precursors, intensive grazing, improved feed conversion, and bST. Mitigation potential at no cost accounts for 26% of total livestock potential. Propionate precursors can reach 59% of abatement potential at no cost. Likewise, 46% of the abatement potential for antimethanogen is also cost-effective.

In 2030, China, India, and Brazil have the highest emissions but are also large sources of potential abatement. The fourth highest emitter is the United States, and it offers the highest abatement potential. China, India, and Brazil can potentially abate 40 $MtCO_2e$, 19 $MtCO_2e$ and 15 $MtCO_2e$, respectively, and the United States' potential reaches 78 $MtCO_2e$. Together the top 3 emitters contribute to a quarter of livestock's abatement potential in 2030. These three countries can reach between 26% and 39% of their individual abatement potential at break-even prices below \$0/tCO_2e, whereas only 1% of the United States' potential can be achieved at break-even prices below \$0/tCO_2e. Using antimethanogens is the measure that offers either the first or second highest abatement potential for each of these countries, which falls in line with the global trend.

Croplands

Emissions from Agricultural Soil Management

Source Background

A number of land management activities add nitrogen to soils, thus increasing the amount of N_2O emitted. Examples of land management activities that directly add nitrogen to soils include:

- Various cropping practices, such as (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) directly depositing wastes by grazing livestock.

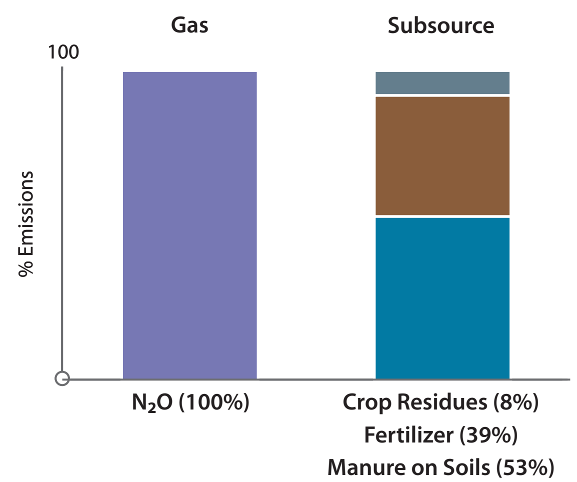
Indirect additions of nitrogen occur through volatilization and atmospheric deposition of ammonia and oxides of nitrogen that originate from (1) the application of fertilizers and livestock wastes onto agricultural land and (2) surface runoff and leaching of nitrogen from these same sources.

Historical Trends

Between 1990 and 2015, N_2O emissions from agricultural soil management increased by 27% because of increased global fertilizer consumption, crop production, and livestock populations. Over this period, total synthetic fertilizer usage in crop production increased by 33%, total crop production increased by 39%, and nitrogen excretion from livestock increased by 19%.

2030 Emissions by Gas and Subsource

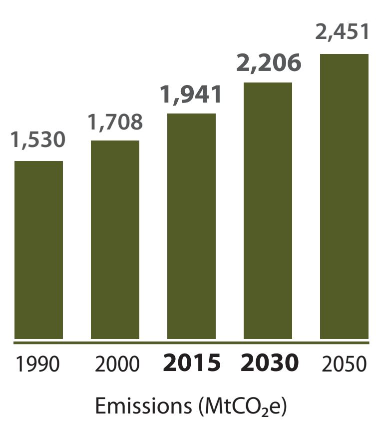
N_2O emissions from agricultural soils include emissions from fertilizer consumption, crop residues incorporated into soils, and manure left on pasture. Manure left on pasture is the primary source of N_2O emissions from agricultural soils, accounting for 53% of emissions in 2030. The share of emissions from fertilizer consumption, crop residues, and manure left on pasture is based on calculated estimates.



Projected Emissions & Top Emitting Countries

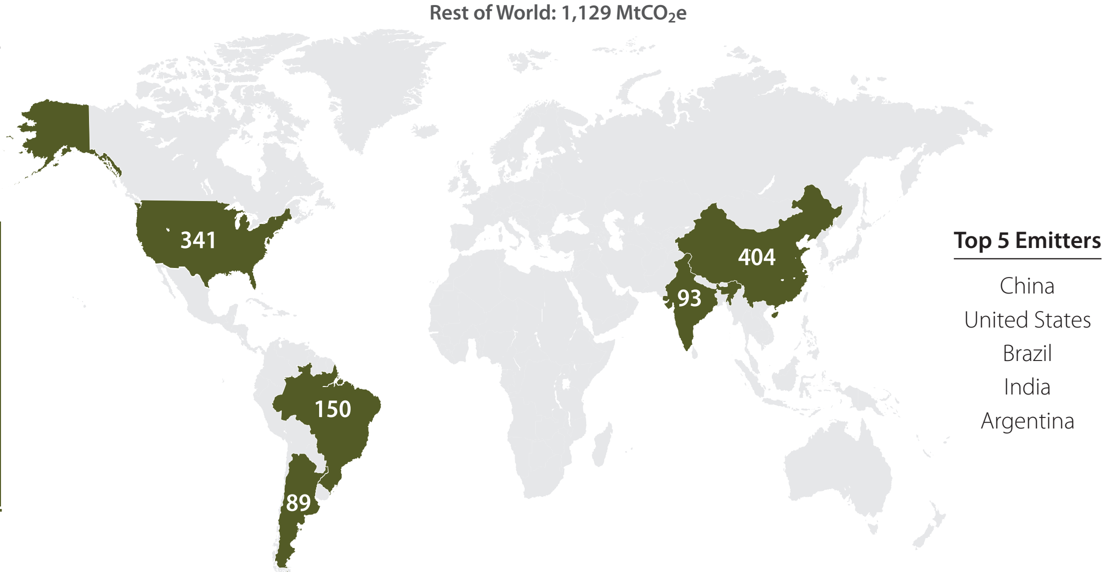
Emissions ($MtCO_2e$)

From 2015 through 2030, N_2O emissions from agricultural soils are projected to increase by 14%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 1,129 $MtCO_2e$



Key Points

- N_2O emissions from agricultural soils are projected to account for 16% of total non-CO_2 emissions by 2030.
- From 1990 through 2015, N_2O emissions from agricultural soils grew roughly in proportion to crop production and fertilizer consumption, and crop production increased in proportion to fertilizer consumption (+39% versus +33%, respectively).
- Under the BAU scenario, emissions are estimated to increase by 14% from 2015 through 2030, in line with the historical trend in emissions.

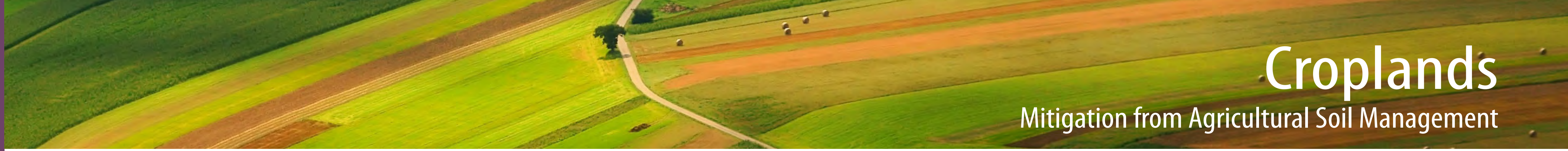
Projected Trends

From 2015 through 2030, N_2O emissions from agricultural soils are projected to increase by 14%. This projection assumes continued increases in crop production, crop area harvested, and fertilizer consumption to support projected increases in global population.[82] Over the projection period, emissions are expected to increase in all regions. The primary factor for the increase in emissions from 2015 through 2030 is increased synthetic fertilizer consumption to meet growing agricultural demand in Africa, the Middle East, Central and South America, and non-OECD Asia.

Emission increases in Africa, the Middle East, and non-OECD Asia are somewhat offset by declining emissions or slower growth in OECD countries (such as Germany and France) because of decreasing livestock populations, economic and environmental agricultural policies, and improved farming practices. Because of the complexities of agricultural product markets and the influences of disruptions in the industry (such as food safety issues), many of these factors are hard to predict.

In Africa, non-OECD Asia, and Central and South America, the anticipated growth from 2015 through 2030 in agricultural soils emissions has several causes. Increases in population and per capita income 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 demand is expected to be met domestically as the agricultural production industry expands.

Emissions from agricultural soils are also influenced by the livestock industry, which also drives the demand for crop production for feed and leads to an increase in the amount of fertilizer and additional nitrogen inputs required to produce feed. In addition, the increased commercialization of the livestock industry is expected to increase livestock production capacity, which leads to increased emissions from livestock manure, the largest estimated component of N_2O emissions for this source category when deposited directly on agricultural soils.



Key Points

- Global emission reduction potential from croplands is 74 $MtCO_2e$ in 2030, or 3% of baseline emissions.
- This analysis considers six abatement options to reduce soil management emissions.
- The implementation of no-till cultivation and reduced fertilizer applications represents 80% of reductions.
- At break-even prices below $0/$tCO_2e$, cropland abatement measures can mitigate 45 $MtCO_2e$ (2% of this source's baseline emissions).

Abatement Measures

This analysis considers six abatement measures for croplands. For the first measure, no-till management, the analysis does not consider any cultivation or field preparation except for seeding. The second analyzed measure is split nitrogen fertilization application, which applies fertilizer 3 times in equal amounts instead of only once on the initial planting day. The third measure is the application of nitrification inhibitors simultaneously with the annual nitrogen fertilizer application, which reduces nitrification by 50% for 8 weeks. The fourth and fifth abatement measures considered the impacts of either increasing or decreasing nitrogen fertilization by 20% above or below the baseline. The final measure, 100% residue incorporation, assumes that all residue remains after harvest and allows for evaluating how reducing residue removal could affect soil organic carbon stocks.

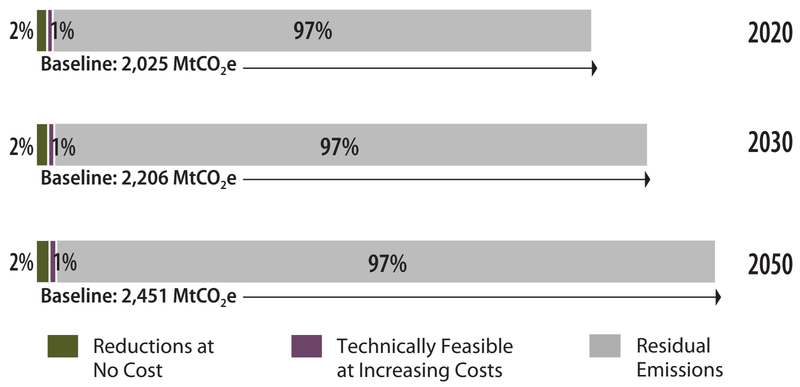
Each of the abatement measures can lower or raise farm costs, depending on changes in farm labor and equipment usage. Use of 100% residue incorporation has no associated costs, and reducing fertilization is expected to lower costs because less fertilizer will be purchased. In contrast, increasing fertilization and split nitrogen fertilization could raise costs because more fertilizer is used and labor increases. Furthermore, using no-till management could lower labor costs because less direct labor is needed due to the reduction in field preparation. However, purchasing equipment for direct planting is a potential increase in capital costs associated with no-till management.

Croplands

Mitigation from Agricultural Soil Management

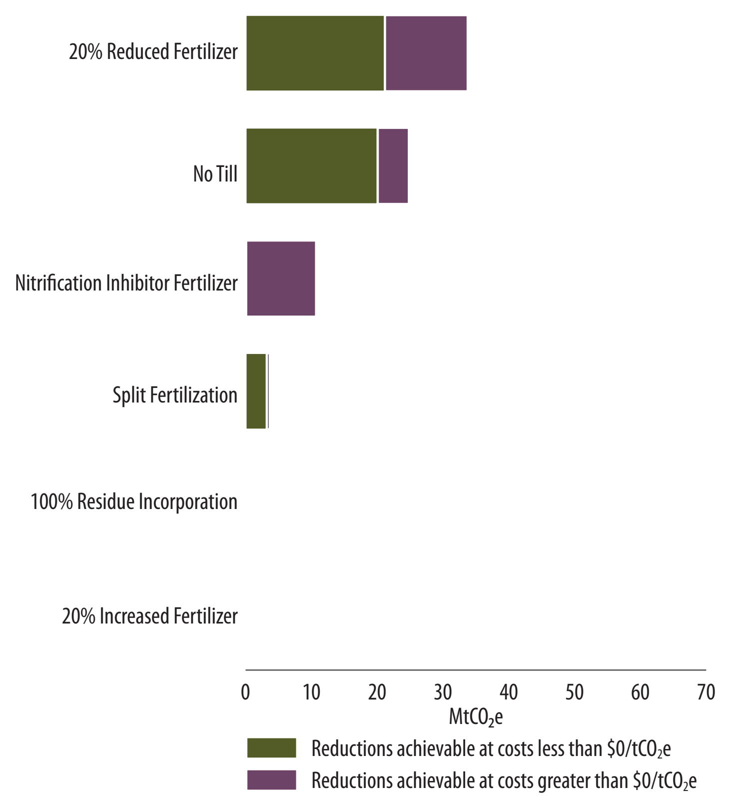
Total Reduction Potential

Potential abatement for non-CO_2 emissions from croplands is small in percentage terms, standing at 3% of baseline emissions in 2030. At a baseline of 2,206 $MtCO_2e$ in 2030, abatement potential amounts to 74 $MtCO_2e$. Roughly two-thirds of abatement potential is feasible at no net cost.



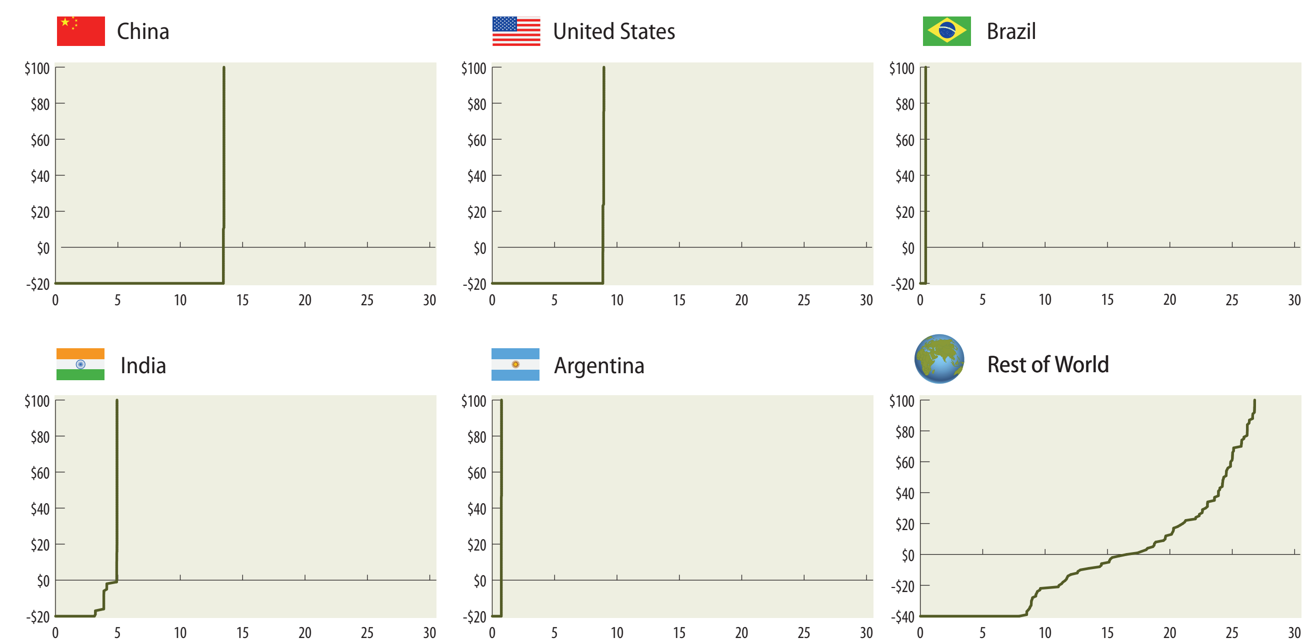
Reduction Potential by Technology

A 20% reduction in fertilizer use represents the largest share of abatement potential from this source globally, responsible for 46% of mitigation in croplands. Across all abatement measures, 61% of abatement potential is available at no cost.



Marginal Abatement Cost Curves, 2030

China and the United States together represent 34% of cropland emissions. Taken together, the top 5 countries in terms of baseline emissions represent 52% of all potential global abatement from this source in 2030.



Abatement Potential

Globally, croplands are responsible for 2,206 $MtCO_2e$ of emissions in 2030. Of these emissions, technology is available to mitigate 3%, or 74 $MtCO_2e$. In 2030, 61% of potential mitigation is available at break-even prices below $0/$tCO_2e$. Additional reductions are possible with the inclusion of more costly abatement measures. For example, mitigation potential increases to 53 $MtCO_2e$ by including abatement measures with an implementation cost less than or equal to $50/$tCO_2e$.

A 20% reduction in fertilizer use represents the largest share of abatement potential from this source globally, responsible for 46% of mitigation in croplands. No-till practices are responsible for 34% of global GHG abatement potential, and nitrification inhibitors provide an additional 15% of abatement potential. The majority of abatement potential for both reduced fertilization and no-till is available at no cost, 63% and 81%, respectively.

In 2030, China, the United States, and India are responsible for the largest abatement potential in croplands, 19%, 16%, and 9%, respectively. In China, 94% of abatement potential, or 14 $MtCO_2e$, is achievable at no cost. In the United States and India, 75% and 70% of abatement, respectively, is cost-effective with no additional incentives. Only 0.05 $MtCO_2e$ of abatement potential in China is achievable at costs between $0 and $20/$tCO_2e$. Similarly, in the United States, almost no additional abatement is achievable at prices between $0/$tCO_2e$ and $20/$tCO_2e$. Similar to global trends, reducing fertilization by 20% is the leading abatement measure for China, the United States, and India, contributing between 50% and 73% of each country's maximum abatement potential.

Several limitations are worth noting in the croplands' analysis. Coverage was limited to major crops. In particular, rice was addressed separately and pasture was excluded. As a result, the mitigation potential, compared with the sector baseline as a whole, is limited.

Rice Cultivation

Source Background

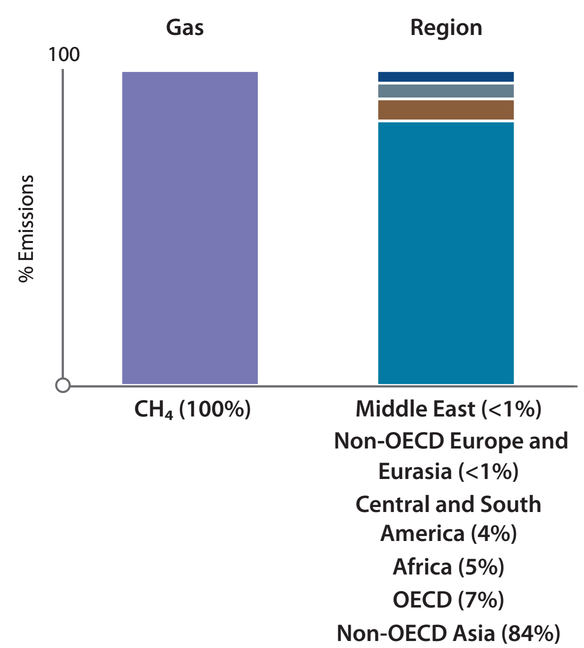
Rice cultivation consists of CH_4 emissions from rice production. The anaerobic decomposition of organic matter (i.e., decomposition in the absence of free oxygen) in flooded rice fields produces CH_4. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present 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.

Historical Trends

Between 1990 and 2015, CH_4 emissions from rice cultivation increased by 4%. Global emissions from rice cultivation increased only slightly from 1990 through 2010 and remained relatively stable through 2015. Underlying this trend is the production of rice in non-OECD Asia. Non-OECD countries in Asia are the primary producers of rice, accounting for over 80% of global emissions from rice cultivation annually from 1990 through 2015. Therefore, rice production in China, India, Vietnam, Indonesia, and Thailand influenced historical trends in emissions from this source.

2030 Emissions by Gas and Subsource

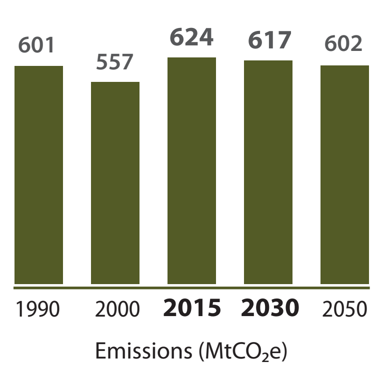
Non-OECD Asia is projected to be the largest source of rice cultivation emissions compared with other regions at 84%. Non-OECD Europe and Eurasia and the Middle East are projected to be the smallest sources of emissions from rice cultivation in 2030 (less than 1% each).



Projected Emissions & Top Emitting Countries

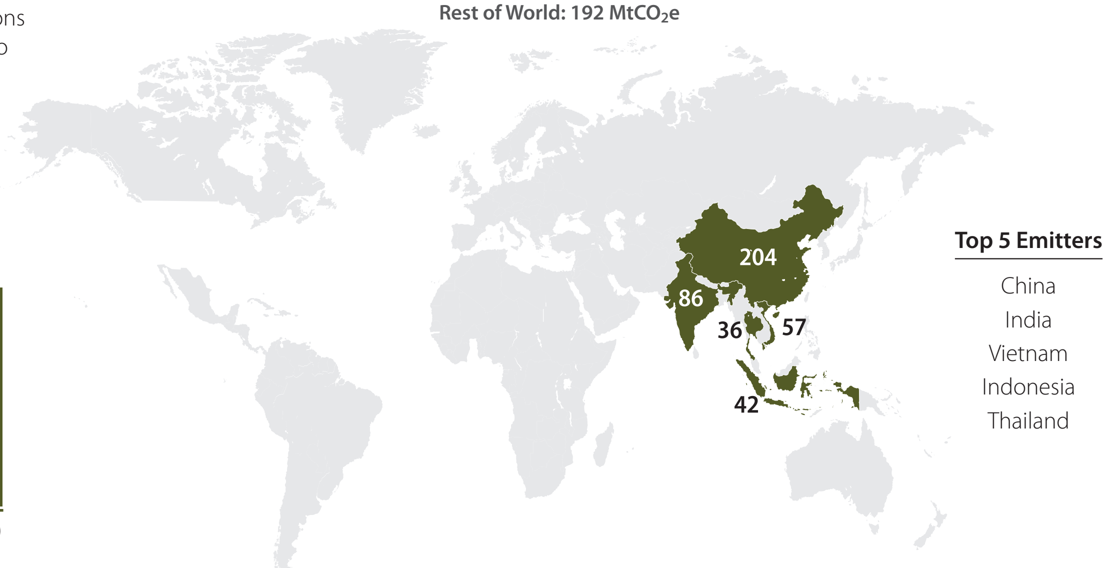
Emissions ($MtCO_2e$)

From 2015 through 2030, CH_4 emissions from rice cultivation are projected to decrease by 1%.



2030 Emissions from Top 5 Emitting Countries

Rest of World: 192 $MtCO_2e$



Key Points

- Rice cultivation is projected to account for 4% of total non-CO_2 emissions by 2030.
- Non-OECD countries in Asia accounted for approximately 84% of global rice cultivation emissions annually from 1990 through 2015.
- From 2015 through 2030, emissions are expected to decrease by 1%, largely due to increases in yield (i.e., rice produced per hectare) and decreased per capita demand for rice in the non-OECD Asia region.

Projected Trends

From 2015 through 2030, CH_4 emissions from rice cultivation are projected to decrease by 1%. This decreasing trend in emissions is driven largely by projected emission reductions in China, one of the top emitting countries for this source across the time series.

This projection assumes an overall decrease in rice area harvested over the projection period. Rice area harvested is the most important determinant of rice CH_4 emissions. Emissions are expected to decrease in non-OECD Asia due to increases in yield, which can decrease the need for area expansion.[83] Emissions are expected to increase in other countries, such as non-OECD countries in Africa, because the demand for rice is expected to increase in these countries to sustain growing populations.

In addition, dietary preferences are also influencing trends in emissions from rice cultivation. As economies grow and middle- to high-income populations increase in non-OECD countries, dietary preferences are expected to shift from rice to protein.[84] This dietary change is expected to reduce the demand for rice and thereby reduce emissions.

The non-OECD Asia region is expected to continue to produce the vast majority of CH_4 emissions from rice cultivation, accounting for approximately 84% of the emissions for this source in 2030. The largest contributors in this region are China and India, which are estimated to be the top emitting countries in 2030. While emissions from multiple countries in the non-OECD Asia region are expected to decrease over the projection period because of the factors described above, emissions from other major emitting countries in non-OECD Asia are expected to increase to meet the growing demand for rice.

Rice Cultivation

Key Points

- The technologically feasible reduction potential from rice cultivation is 221 MtCO$_2$e in 2030, 36% of baseline emissions.
- India is the second highest emitter but offers the highest global abatement potential.
- Cost-effective abatement potential ($0 break-even price) is 62 MtCO$_2$e, or 28% of total abatement potential.
- A $20 break-even price contributes to 54% of the rice cultivation abatement potential in 2030.

Abatement Measures

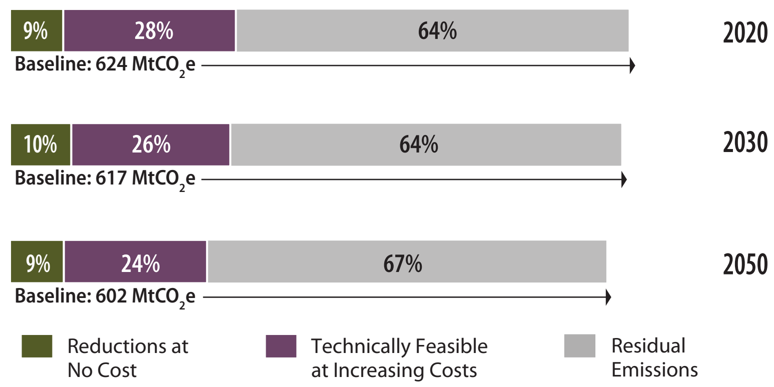
For rice cultivation, this analysis considered five management categories with various application techniques: paddy flooding (continuous flooding, midseason drainage [MD], alternating wetting and drying [AWD], and dryland production), crop residue incorporation (50% and 100%), tillage (conventional and no-till), fertilization application (conventional, ammonium sulfate, nitrification inhibitor, slow-release, reduced use, and auto-fertilization), and direct seeding. Rather than considering each management technique separately, the analysis combined different techniques to assess the best combinations to abate emissions from rice cultivation.

Different management methods can be applied to rain-fed or irrigated fields and, in some cases, both. For paddy flooding, mid-season draining and alternating between wetting and drying are applicable to irrigated rice. In contrast, continuous flooding and use of dryland production are applicable to both field types. Farmers use direct seeding in both field types by flooding the rice paddy 40 days after planting and draining the field 10 days before harvesting.

Properly managing tillage, residue, and fertilizer techniques is crucial for growing a quality crop while reducing GHG emissions. Conventional tillage tills 20 cm deep before the first crop rotation and 10 cm deep for following rotations, whereas no-till mulches the residue and does not till the land. Residue incorporation leaves either 50% or 100% of the above-ground residue to be incorporated in the next tillage. Nitrogen fertilizers are applied in the form of urea or ammonium sulfate and sometimes alongside nitrogen inhibitors.

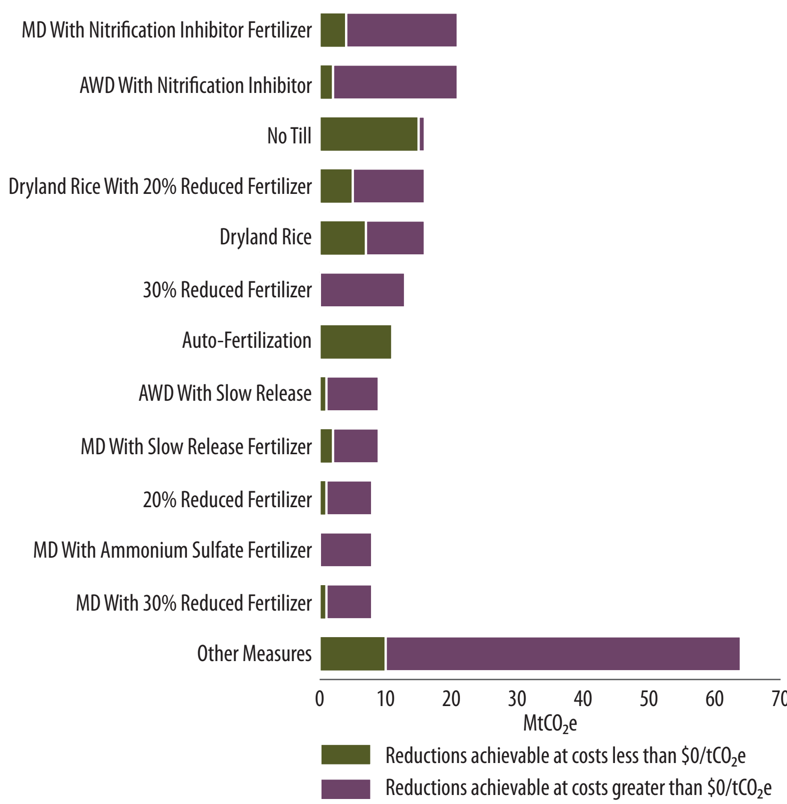
Total Reduction Potential

Abatement potential is 221 MtCO$_2$e in 2030, 38% of which is feasible at no cost.. Note that the baseline of 617 MtCO$_2$e includes only CH$_4$ emissions; N$_2$O emissions from rice cultivation are included in the croplands section baseline.



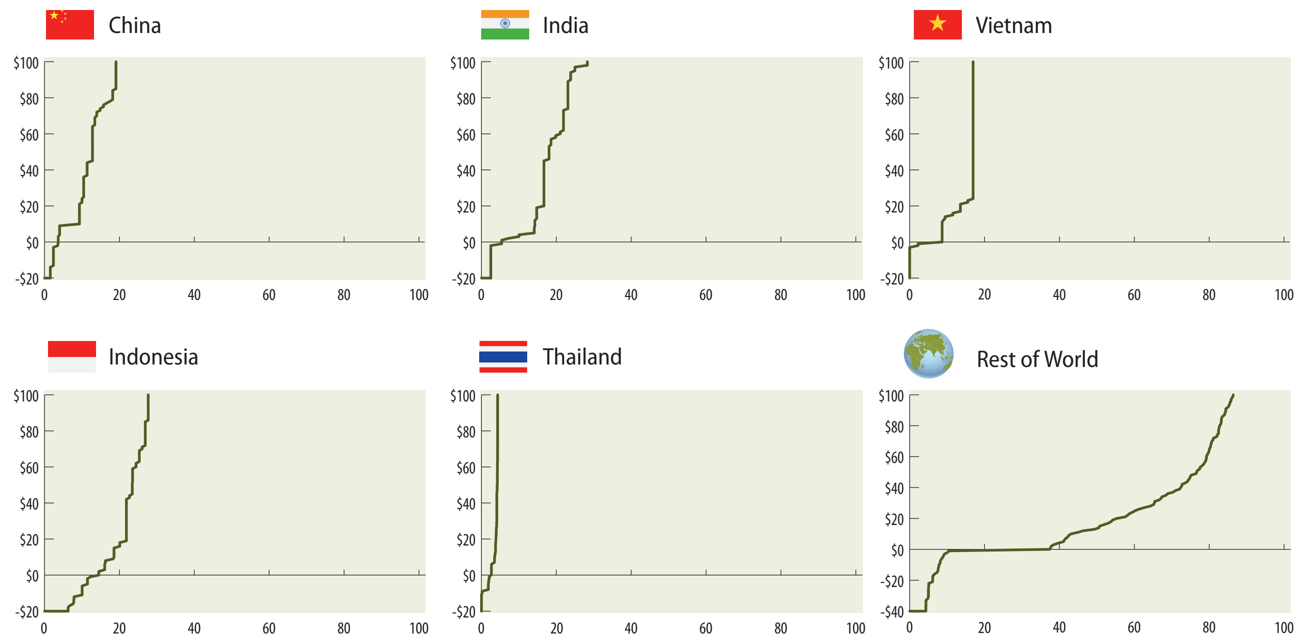
Reduction Potential by Technology

A total of 36 abatement measures were modeled for rice cultivation, but the top 10 measures comprise 64% of abatement potential. Across all abatement measures, 28% of abatement is available at costs below $0/tCO$_2$e.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of emissions represent 69% of baseline emissions from rice cultivation and 55% of abatement potential. China, the top emitting country, represents 33% of baseline emissions alone.



Abatement Potential

To estimate abatement potential for this analysis, we used a modified version of the DNDC 9.5 global database to simulate crop yields and GHG fluxes from global paddy rice cultivation systems. The model estimates GHG fluxes (CH$_4$, direct and indirect N$_2$O) and changes in soil organic carbon. As a result, the mitigation potential reflects reductions in CH$_4$, N$_2$O, and CO$_2$.

Many of the rice cultivation management techniques focus on increasing soil carbon sequestration, but sequestration capacity is limited. As soils reach their maximum ability to sequester carbon, mitigation may decline over time. This bears out in the modeling results, which estimate a maximum mitigation potential of 221 MtCO$_2$e in 2030, 211 MtCO$_2$e in 2040, and 198 MtCO$_2$e in 2050. Nonetheless, roughly half of the available abatement can be achieved at relatively low prices. Approximately 28% of the potential abatement, or 62 MtCO$_2$e, can be abated at prices below $0/tCO$_2$e in 2030 with an additional 26% reduction from baseline available at prices between $0 and $20/tCO$_2$e.

Globally, using mid-season drainage with nitrification inhibitor fertilizer is the management technique with the highest abatement potential in 2030. This measure has the potential to cost-effectively deliver 4 MtCO$_2$e and offers an additional 17 MtCO$_2$e for break-even prices above $0/tCO$_2$e. The second management technique with the highest abatement potential is alternating wet and dry with nitrification inhibitor. This abatement measure can potentially mitigate 20 MtCO$_2$e in 2030, which is 3% of baseline emissions.

China, India, Vietnam, and Indonesia are the top 4 emitters from rice cultivation and are valuable sources of potential abatement. In 2030, each country can abate between 24 MtCO$_2$e and 38 MtCO$_2$e, respectively. Furthermore, 55% of rice cultivation's global abatement potential in 2030 comes from these four countries, 17% directly from India. All four nations offer cost-effective mitigation options. At break-even prices less than $0/tCO$_2$e, India and Vietnam abate 14% and 27% of their national potential, respectively, while Indonesia abates 48%.

WASTE

Introduction

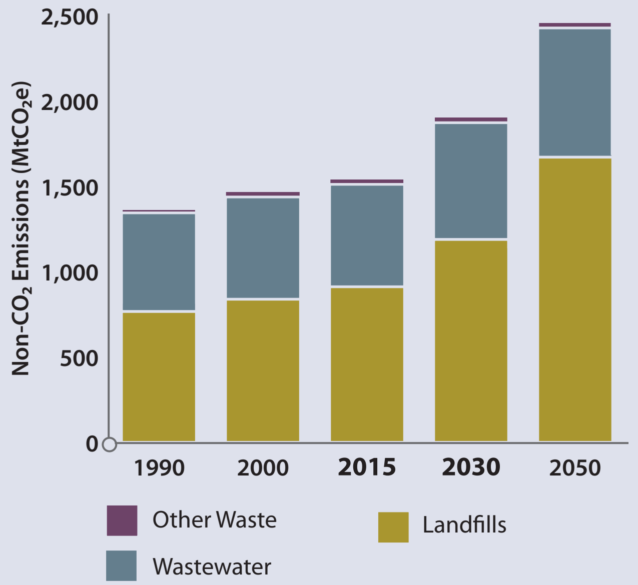
The waste sector is the third largest contributing sector to global emissions of non-CO_2 GHGs, accounting for 13% of global non-CO_2 emissions in 2015. This section presents global waste-sector CH_4 and N_2O historical and projected emissions and the mitigation potential from the following source categories:

- Landfills (CH_4)
- Wastewater (CH_4, N_2O)

Projections and MAC curves were estimated for all sources. Emissions from landfills increased 19% between 1990 and 2015, growing from 56% to 59% of emissions from the waste sector during this time frame. Waste-sector emissions increased 13% between 1990 and 2015.

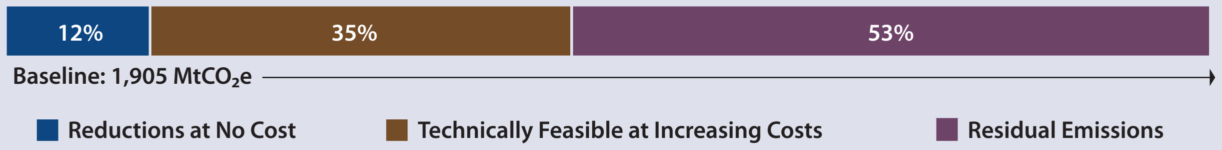
Between 2015 and 2030, emissions from landfills are projected to grow more quickly than emissions from wastewater, increasing 30% compared with 14% growth for wastewater. During this time period, global waste-sector emissions are projected to increase 23% under a BAU scenario, reaching 1,905 $MtCO_2e$ in 2030. Increases in population and per capita waste generation drive global waste emissions upward, but historical implementation of waste-related regulations and gas recovery and use has tempered this increase.

Historical and Projected Emissions from the Waste Sector



Mitigation potential from the waste sector is estimated to be approximately 887 $MtCO_2e$ in 2030. This mitigation potential is 53% and 37% of landfill and wastewater emissions, respectively; 47% of waste-sector emissions; and 23% of total global non-CO_2 mitigation potential in that year.

Emission Reduction Potential, 2030



Landfills

Source Background

Landfilling of solid waste includes emissions associated with the disposal of municipal solid waste (MSW) and industrial solid waste. Landfills produce CH_4 and other landfill gases, primarily CO_2, through the natural process of bacterial decomposition of organic waste under anaerobic conditions. Landfill gases are then generated over a period of several decades, with flows usually beginning within 2 years of disposal.

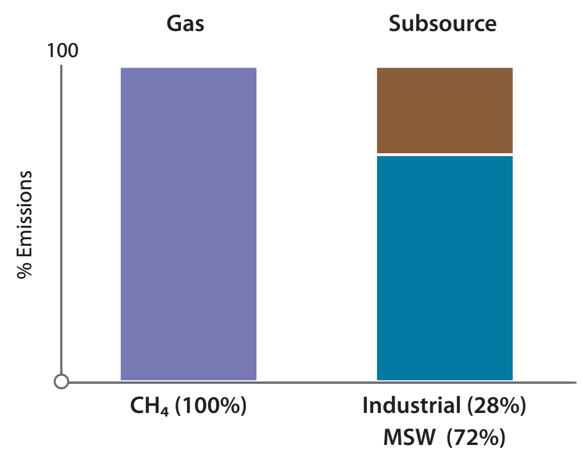
Historical Trends

Solid waste was the fifth largest contributor to global emissions of non-CO_2 GHGs in 2015, accounting for about 8% of total emissions. The amount of CH_4 generated by landfills is determined by key factors including population, the quantity of waste disposed of per person, composition of the waste disposed of, and the waste management practices applied at the landfill.

Between 1990 and 2015, global CH_4 emissions from landfills increased by about 19%. Over this period, landfill-related emissions decreased in the European Union and other developed countries by approximately 32%, driven by large reductions in the use of landfills for final disposal combined with increased deployment of landfill gas recovery. The overall growth in global landfill emissions during the past 25 years has been driven by population growth, economic development, and urbanization in developing countries.

2030 Emissions by Gas and Subsource

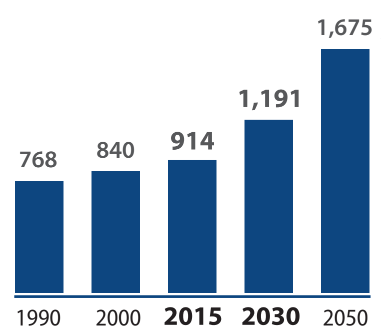
MSW includes household, garden and park, commercial, and institutional waste. Industrial waste includes organic process waste generated by industry, which is not collected in the MSW stream. MSW is the primary source of landfill CH_4 emissions, accounting for between 70% and 80% of emissions from landfilling from 1990 through 2030.[85]



Projected Emissions & Top Emitting Countries

Emissions (MtCO$_2$e)

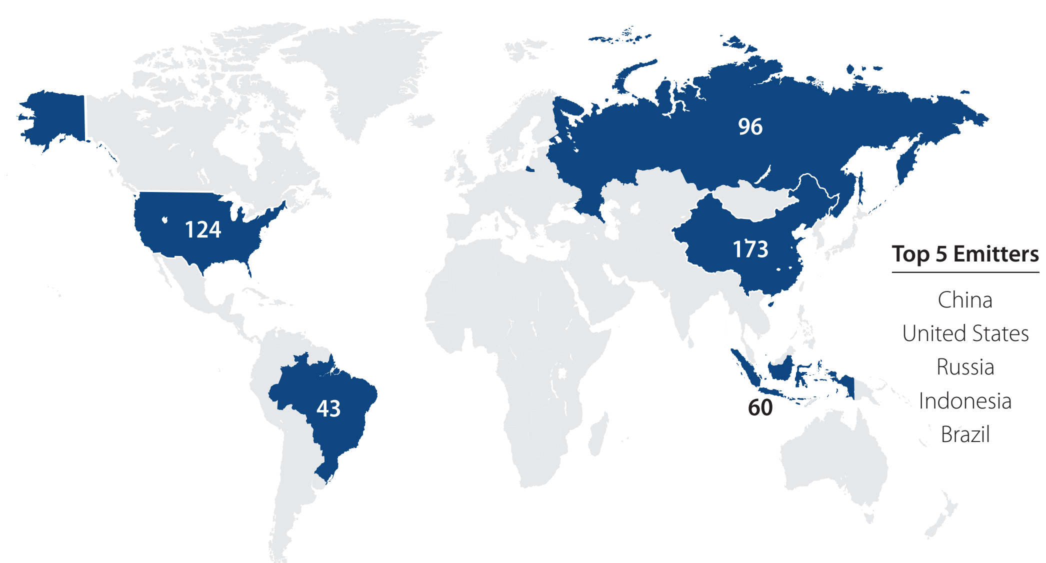
From 2015 through 2030, CH_4 emissions from landfills are projected to increase by 30%.



Emissions (MtCO$_2$e)

2030 Emissions from Top 5 Emitting Countries

Rest of World: 695 MtCO$_2$e



Key Points

- **Between 1990 and 2015, global CH_4 emissions from landfilling of solid waste increased by 19%.**
- **Landfill emissions are estimated to increase by an additional 30%, accounting for about 9% of global BAU emissions in 2030.**
- **Driving factors for landfill emission trends include growing populations, increases in personal income, and urbanization.**

Projected Trends

Despite stable or even increased waste generation in many OECD countries, landfill emissions from OECD countries are projected to remain relatively flat, increasing about 4% from 2015 through 2030, with an associated decrease in their global contribution to total landfill emissions from 32% to 25% by 2030. The decline in the proportion of landfill emissions from OECD countries is due to this region's relatively lower population growth and use of landfill disposal compared with other regions. The landfill emission projection methodology assumes constant per capita waste generation and landfill disposal proportions over time, based on the most recently available country-reported or IPCC default data. The projections, therefore, capture the effect of current practices (i.e., based on policies and programs implemented historically, such as landfill gas collection policies or programs to limit the quantity of organic waste that can enter solid waste facilities) but do not include additional, future measures. Differences in projected emissions across regions are driven primarily by differences in current waste management practices and future population growth.

In other regions, emissions from landfilling solid waste are projected to increase at a greater rate. Regions showing high growth in landfill emissions between 2015 and 2030 include Asia with an estimated 56% increase in emissions by 2030, Africa (42%), and Central and South America (36% and 24%, respectively). Asia's contribution to global emissions is projected to increase to nearly 50% by 2030 compared with a 35% contribution in 2015. The combined effects of rapid economic change, expansive growth policies, and population growth, particularly in urban centers, are expected to increase consumption, leading to higher waste generation. In addition, to improve overall waste management, these regions are expected to transition from open or otherwise unmanaged dumpsites to managed landfills, thereby increasing landfill gas production and potential emissions from landfills.

Landfills

Key Points

- Global abatement potential from landfills is 636 $MtCO_2e$, or 53% of projected baseline emissions in 2030.
- Abatement measures with costs below $0/$tCO_2e$ can achieve a 19% reduction in landfill baseline emissions.
- Electricity generation with a reciprocating engine is the leading abatement measure in 2030, accounting for 12% of potential.

Abatement Measures

This analysis considers 12 abatement options to control landfill emissions, which are grouped into three categories: (1) collection and flaring, (2) landfill gas (LFG) utilization systems (LFG capture for energy use), and (3) enhanced waste diversion practices (e.g., recycling and reuse programs).

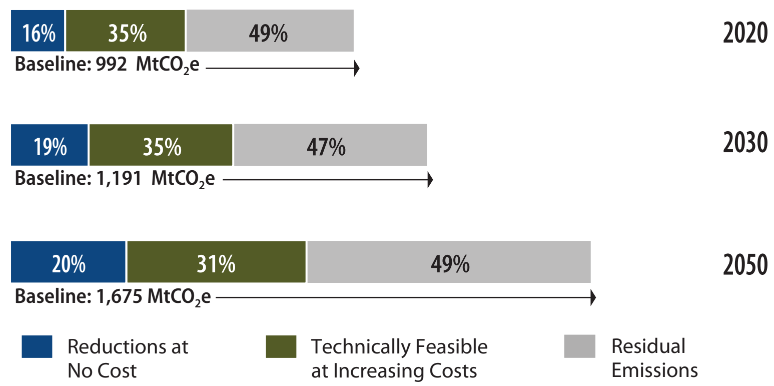
Collection of LFG is feasible at most engineered landfills. It prevents high concentrations of gas in the landfill, which addresses public health and facility safety concerns. After collecting LFG, the least capital-intensive way to reduce emissions is flaring, which burns off the gas. However, flaring does not deliver any economic benefits for landfill operators.

Energy production represents a potential revenue stream for landfills. It includes electricity generation, anaerobic digestion, and direct use. A variety of engine types and waste-to-energy processes can achieve electricity generation. Anaerobic digestion provides CH_4 for on-site electricity or for selling to the market. Direct use implies that a landfill transports captured methane to a facility, which uses it for electricity generation, as process heat, or as an input into other processes.

Furthermore, enhanced waste diversion practices redirect biodegradable components of the waste stream from the landfill for reuse through recycling or conversion to a value-added product (e.g., energy or compost). Diverting organic waste components lowers the amount of CH_4 generated at the landfill. Other benefits from the measures under this category include the sale of recyclables, electricity, and cost savings in avoided tipping fees.

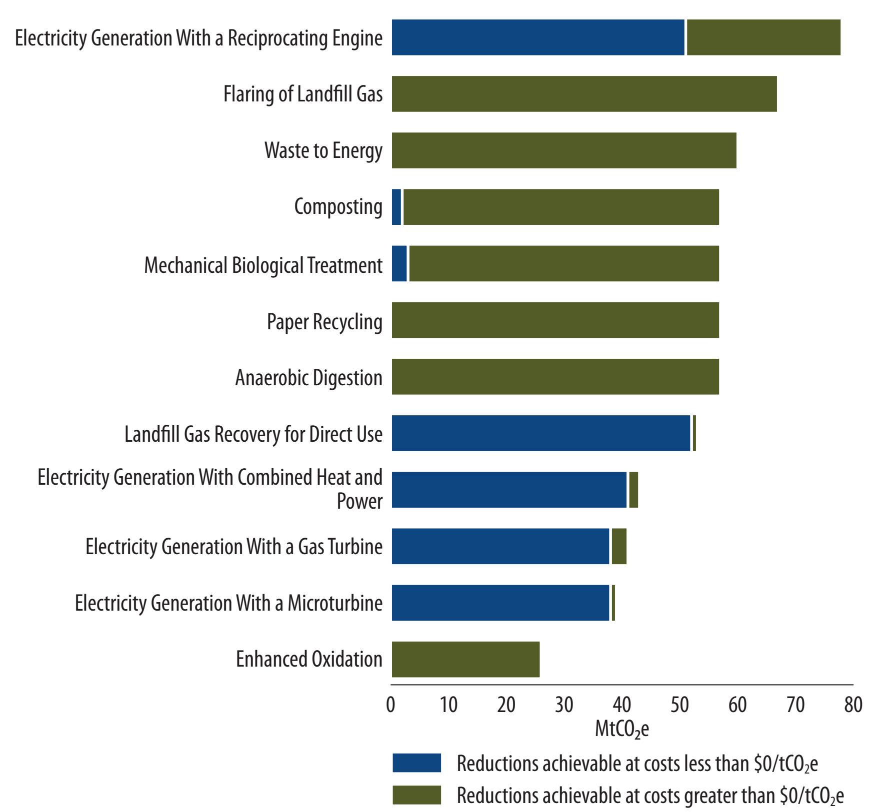
Total Reduction Potential

Reducing emissions by 16% compared with the 2020 baseline is cost-effective. An additional 35% reduction is available using technologies with increasingly higher costs. The cost-effective reduction potential rises to 19% in 2030 and to 20% in 2050.



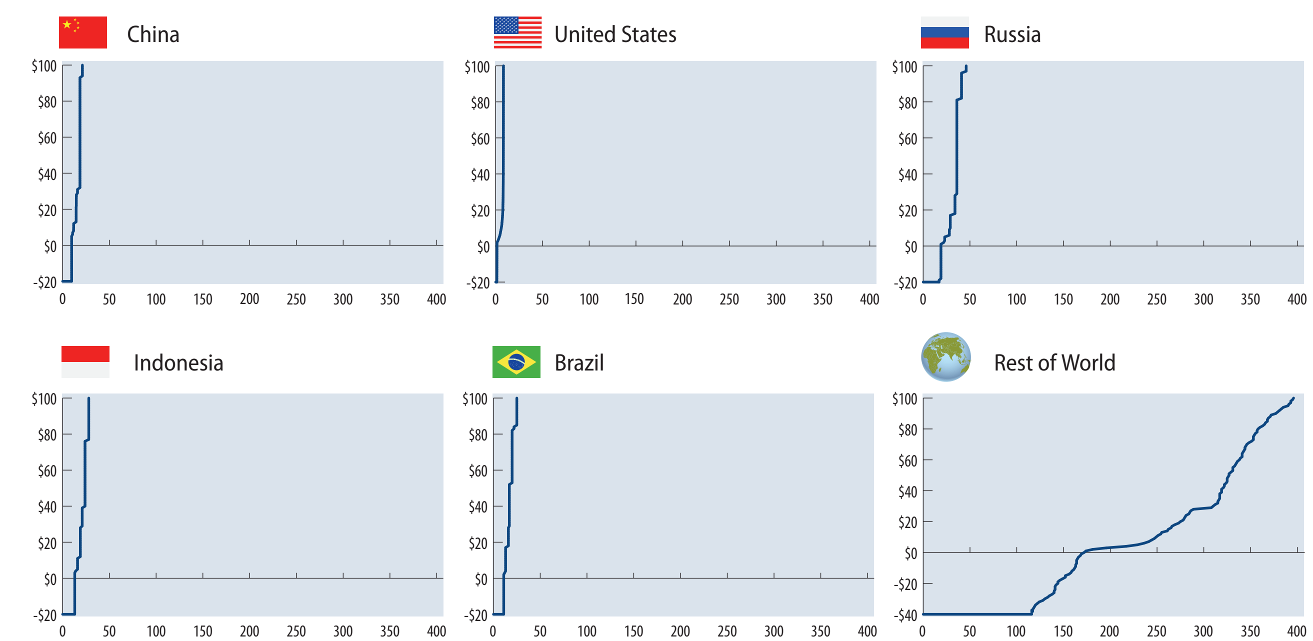
Reduction Potential by Technology

In 2030, landfill gas recovery for direct use is the leading emission abatement measure at $0/$tCO_2e$; flaring offers the highest abatement potential at higher prices. Overall, electricity generation measures comprise the largest share of potential abatement with 78 $MtCO_2e$.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of emissions represent 23% of all potential global abatement from landfills in 2030. The United States is the second largest emitter in the world, but its maximum potential abatement is lower compared with other countries because of high levels of prior adoption of abatement measures.



Abatement Potential

Global abatement potential from solid waste landfills is estimated to be approximately 635 $MtCO_2e$ in 2030, or 53% of the baseline emissions. Slightly more than half of all potential abatement can be achieved at break-even prices below $20/$tCO_2e$; 31% of reductions can be achieved at prices below $0/$tCO_2e$, suggesting a substantial share of abatement could generate revenue for landfill operators.

At a global level in 2030, the measures that contribute the highest potential to reduce emissions are electricity generation with a reciprocating engine (78 $MtCO_2e$), flaring of LFG (67 $MtCO_2e$), and waste to energy (60 $MtCO_2e$). Other types of energy generation (electricity using combined heat and power, gas turbines or microturbines, and direct use of LFG) add an additional 123 $MtCO_2e$ of abatement potential. Other enhanced waste diversion practices represent 307 $MtCO_2e$ of potential abatement.

Russia, Indonesia, and Brazil have the highest abatement potential, contributing to 18% of the global potential in 2030. These nations are the third, fourth, and fifth top emitters. Russia's, Indonesia's, and Brazil's mitigation potential from landfills is 51 $MtCO_2e$, 35 $MtCO_2e$, and 28 $MtCO_2e$, respectively. These nations can reach between 20% and 26% of national potential with break-even prices below $0/$tCO_2e$.

China and the United States are the top 2 emitters and collectively can mitigate 5% of total landfill emissions in 2030—27 $MtCO_2e$ in China and 8 $MtCO_2e$ in the United States. The United States already has a high rate of adoption of abatement measures, leading to a lower future mitigation potential.

Wastewater

Key Points

- Wastewater emissions are estimated to increase by 14% from 2015 through 2030, accounting for 5% of global non-CO_2 emissions in 2030.
- Projected emissions reflect population growth and an increasing contribution of emissions from fast-growing urban populations.
- The countries with the highest emissions are China, Indonesia, and India in 2030.

Source Background

Wastewater originates from a variety of residential, commercial, and industrial sources. It can be a source of CH_4 when organic material present in the wastewater-flows decomposes under anaerobic conditions. Developed countries rely on centralized aerobic wastewater treatment systems that limit CH_4 generation, while developing countries often rely on a broader suite of wastewater treatment technologies. N_2O emissions occur primarily as indirect emissions from wastewater after disposal of effluent into waterways, lakes, or the sea.

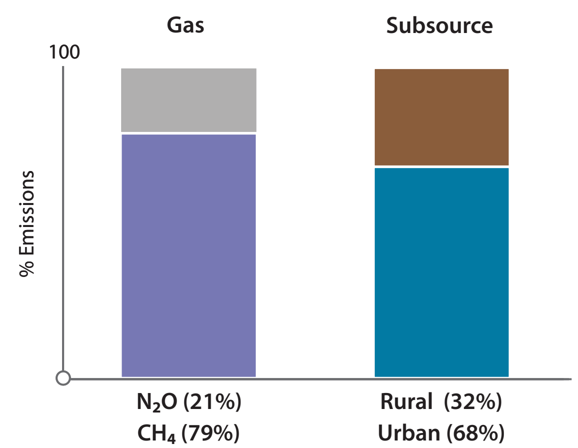
The quantity of degradable organic material in the wastewater and the type of treatment system are the key drivers of wastewater CH_4 emissions. The nitrogen content in the wastewater effluent is the key driver for indirect N_2O emissions.

Historical Trends

Wastewater accounted for 5% of global non-CO_2 emissions in 2015. Between 1990 and 2015, global CH_4 and N_2O emissions from wastewater disposal and treatment increased by 4%. CH_4 emissions decreased by 6% during this period, whereas indirect N_2O emissions increased substantially on a percentage basis over the same period—69%. Since 1990, the share of wastewater emissions from large urban populations with more access to wastewater treatment has increased compared to the emissions from rural areas, as urbanization has increased globally.

2030 Emissions by Gas and Subsource

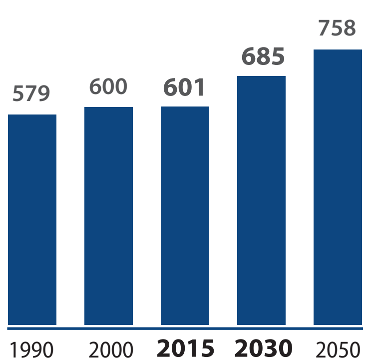
CH_4 emissions account for about 79% of projected wastewater emissions, while N_2O emissions account for the remaining 21%. Urban wastewater emissions are projected to increase by nearly 2% per year compared with a decrease of 0.3% annually for rural wastewater emissions.[86]



Projected Emissions & Top Emitting Countries

Emissions ($MtCO_2e$)

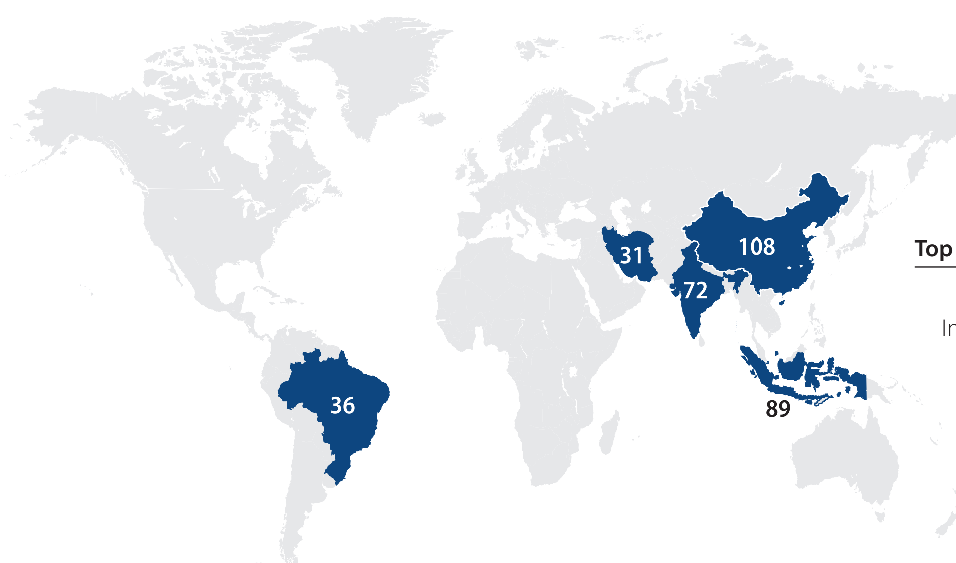
From 2015 through 2030, global wastewater emissions (CH_4 and N_2O) are projected to increase by 14%.



Emissions ($MtCO_2e$)

2030 Emissions from Top 5 Emitting Countries

Rest of World: 349 $MtCO_2e$



Projected Trends

Global wastewater emissions are projected to increase modestly on an annual basis at a rate of less than 1% per year from 2015 through 2030. The emission projections demonstrate a continued shift from rural to urban sources of emissions. In 1990, rural populations were the majority source of wastewater emissions, at approximately 55%. Since that time, the share of urban emissions increased steadily to 62% in 2015 and is expected to continue increasing to 68% through 2030. The global urban population is expected to increase by 28% from 2015 through 2030, while rural populations are estimated to increase by approximately 1% over the same period.

Although total wastewater emissions are projected to increase, the overall mix of the largest country emitters is stable from 2015 through 2030. Future growth is projected to come from developing countries with fast-growing urban populations. In addition to seeing the most population growth, urbanizing areas tend to see the largest increases in utilization of wastewater collection and treatment technologies, which have higher emission factors in many cases than open disposal (e.g., latrines) but provide substantial public health and sanitation benefits. This combination of factors is reflected in the data that show future growth in wastewater emissions coming from urban populations, whereas emissions from rural populations decrease in the projections.

Wastewater

Key Points

- The maximum abatement potential in 2015 is 122 $MtCO_2e$, or 20% of projected emissions.
- By 2030, the abatement potential is expected to reach 251 $MtCO_2e$, or 37% of the projected baseline.
- Close to 10% of baseline emissions can be abated at break-even prices of less than $50/$tCO_2e$.

Abatement Measures

Upgrades to infrastructure and equipment can reduce CH_4 emissions from wastewater. No proven and reliable technologies for mitigating N_2O from wastewater treatment exist. Abatement measures available for wastewater include (1) implementing centralized collection of wastewater for treatment, (2) constructing aerobic wastewater treatment plants (WWTPs), and (3) constructing anaerobic WWTPs with cogeneration.

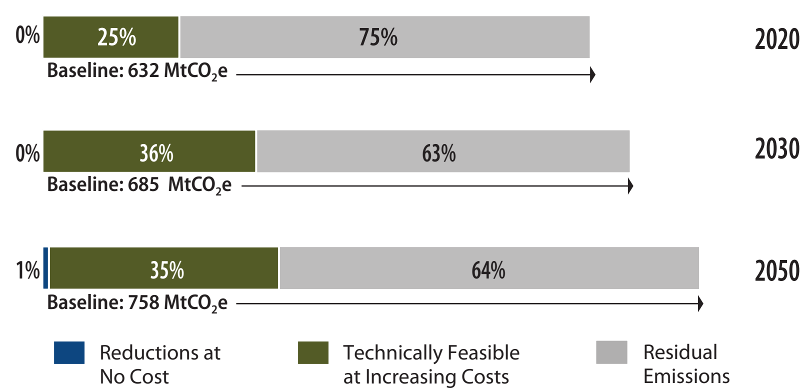
Country-specific factors, including economic resources, population density, government, and technical capabilities, are important in determining the mitigation potential for this source. A country's desire and capacity for improved sanitation are the primary drivers of the adoption of these technologies, and CH_4 mitigation is a secondary result. This analysis does not include the value of health benefits resulting from improved sanitation, which may affect the mitigation estimates.

This report quantifies the mitigation potential of replacing latrines, open sewers, and septic tank use with anaerobic WWTPs. These three infrastructure improvements provide a significant amount of mitigation for costs below and above $0/$tCO_2e$. Replacing latrines offers the highest abatement potential because they are better than using no sewage treatment. Latrines are common in developing countries, presenting a low-cost abatement option.

This analysis also considers the mitigation potential of a WWTP that uses an anaerobic sludge digester with co-generation. However, adding co-generation increases the capital cost of the technology. Thus, this measure is found mostly in developed countries.

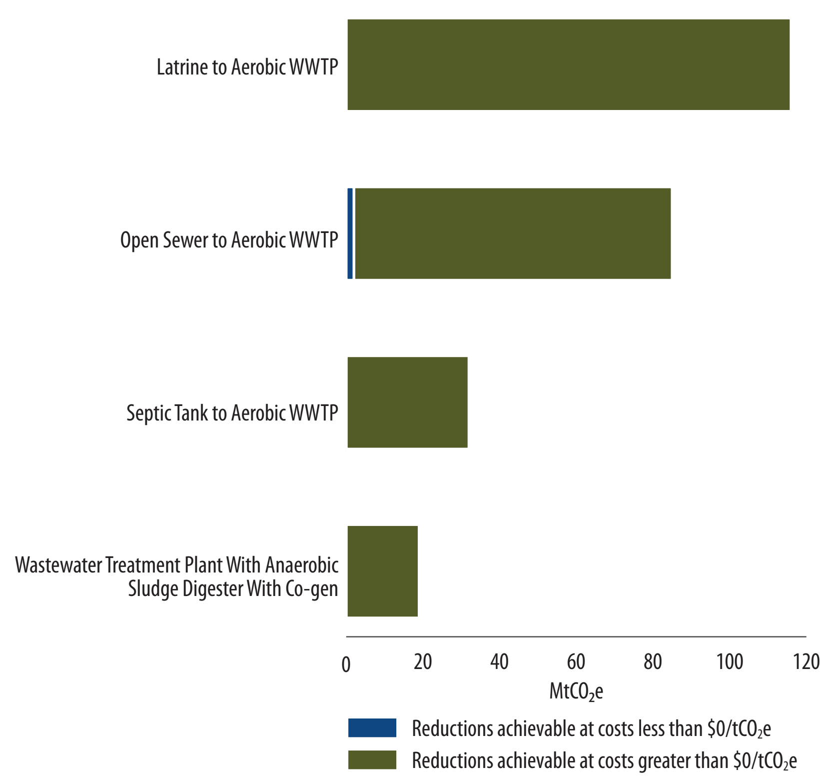
Total Reduction Potential

There are no emission reductions available from wastewater at prices below $0/$tCO_2e$ in 2020. At increasing costs, a 25% reduction in emissions is possible. The emissions reduction potential at increasing costs rises to 36% in 2030.



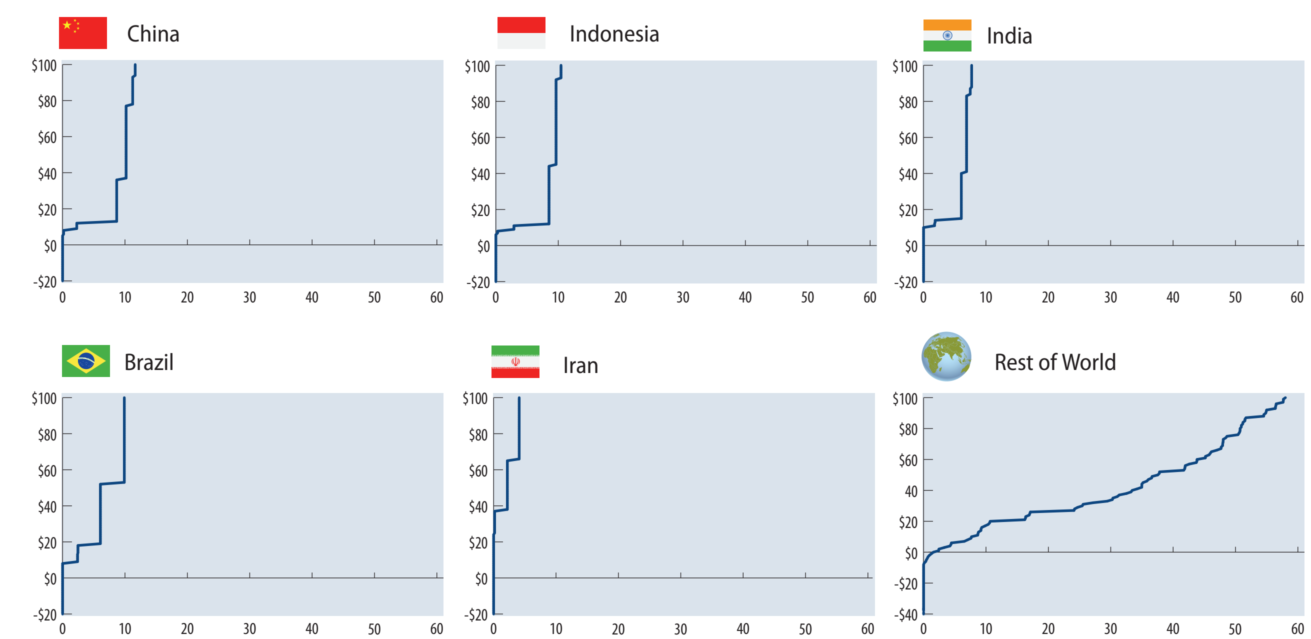
Reduction Potential by Technology

In 2030, switching from latrines to aerobic WWTPs is the leading emission abatement measure with the potential to reduce emissions by 116 $MtCO_2e$. Switching from open sewers to aerobic WWTPs is the only measure that offers reductions at costs less than $0/$tCO_2e$.



Marginal Abatement Cost Curves, 2030

Taken together, the top 5 countries in terms of baseline emissions represent 48% of all potential global abatement for this source in 2030. China is the highest emitting country but also contributes to 16% of global abatement potential for this source, or 39 $MtCO_2e$, in 2030.



Abatement Potential

The global abatement potential of CH_4 from wastewater treatment is 122 $MtCO_2e$ in 2015 and rises to 251 $MtCO_2e$ in 2030. High-cost abatement measures from wastewater treatment significantly constrain the abatement achievable at lower prices. Cost-effective emission reductions, or reduction at prices below $0, are limited to 2 $MtCO_2e$, less than 1% of BAU emissions in 2030.

At the global level, the top abatement measures require shifting from using latrines and open sewers to implementing centralized collection with aerobic WWTPs. The installation of these plants costs $97 million per plant and has an annual maintenance cost of $4.7 million, making these an expensive abatement option. However, the improved sanitation and mitigation potential makes aerobic WWTPs worthwhile investments. Shifting from latrine use to aerobic WWTP has the highest mitigation potential, reaching 116 $MtCO_2e$, or 17% of baseline emissions. Shifting from using open sewers to using aerobic WWTPs is the second-best abatement measure and has the potential to abate 85 $MtCO_2e$ in 2030. All abatement measures from wastewater offer 60% to 80% reduction efficiency.

China, Indonesia, and India are the countries with the highest mitigation potential in 2030 across all abatement measures. These countries have the potential to mitigate 39 $MtCO_2e$, 32 $MtCO_2e$, and 26 $MtCO_2e$, respectively. The three countries contribute to 39% of the global abatement potential, with 16% coming from just China. None of these countries have cost-effective abatement measures at a zero price; however, each country can potentially reach 22% to 27% of its mitigation potential with break-even prices less than $20/$tCO_2e$. Switching from latrine usage to aerobic WWTP is the leading abatement measure for all three countries. This measure can potentially mitigate 29 $MtCO_2e$ in China and drive 74% of that nation's overall potential in 2030. Switching from open sewer usage to aerobic WWTPs is the second most influential abatement technology in each of these countries.

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3 See endnote 1.

4 U.S. Environmental Protection Agency. 2013. *Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030*. EPA #430 R-13-011. Washington, DC: EPA. Available online at https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-mitigation-non-co2-ghgs-report-download-report

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7 U.S. Environmental Protection Agency. 2005. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020*. Washington, DC: EPA.

8 See endnote 1.

9 See endnote 2.

10 See endnote 4.

11 Although this document is published by the EPA, the U.S. projections were generated using the same methodologies used for all countries. The BAU projection does not explicitly model the effects of current or proposed policies.

12 Historical reported emission estimates are available at varying years for each country between 1990 and 2016.

13 Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

14 Disaggregation of CH_4 from coal mining by mine type was based on default IPCC emissions factors and may not be consistent with country-reported data.

15 U.S. Energy Information Administration. 2017. International Energy Outlook 2017. DOE/EIA-0484(2017). Washington, DC: Energy Information Administration, U.S. Department of Energy. Available online at https://www.eia.gov/outlooks/ieo/

16 Emissions from the energy sector were projected using data from EIA's International Energy Outlook Reference Case scenario. This EIA scenario considers current policies and incorporates certain specific details of commitments under international climate agreements such as renewable energy and energy mix goals, but uncertainties about how commitments would be implemented or achieved can limit the extent to which each can be modeled in EIA's projections.

17 See endnote 15.

18 Ibid.

19 Disaggregation of CH_4 from natural gas and oil systems by industry segment was based on default calculations and may not be consistent with country-reported data.

20 See endnote 15.

21 International voluntary programs encourage efforts to reduce CH_4 emissions without reducing energy production, and progress has been made historically to control these emissions. Mitigation efforts were included in the BAU projection to the extent they are included in historical country-reported inventories, but the projections do not model future changes in control from policies or voluntary actions. For example, at the time of this writing, the United States is considering changes to New Source Performance Standards (NSPS) that affect emissions from natural gas and oil systems, but the projections in this report do not model either current or proposed policies, and more granular analysis would be required to assess policy impacts such as the NSPS.

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26 Biomass fuels include wood fuel, charcoal, agricultural residues and waste, and municipal waste.

27 Unlike CO_2 emissions, biomass combustion does in all cases result in net additions of CH_4 and N_2O to the atmosphere.

28 See endnote 16.

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30 Disaggregation of CH_4 and N_2O emissions from combustion by fuel type was based on default calculations and may not be consistent with country-reported data.

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32 Ibid.

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34 Ibid.

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40 ICIS. April 2013. *Asia chemical profile: Adipic acid.* ICIS Chemical Business. Available online at https://www.icis.com/resources/news/2013/04/20/9660653/asia-chemical-profile-adipic-acid/

41 See endnote 37.

42 Disaggregation of N_2O from this source category into nitric versus adipic acid production was based on default calculations and may not be consistent with country-reported data.

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United States Environmental Protection Agency
Office of Atmospheric Programs (6207A)
Washington, DC 20005