



Global Mitigation of Non-CO₂ Greenhouse Gases





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Contents

Section	Page
Executive Summary.....	ES-1
I. Technical Summary	
I.1 Overview.....	I-1
I.2 Non-CO₂ Greenhouse Gases.....	I-1
I.2.1 Methane (CH ₄)	I-2
I.2.2 Nitrous Oxide (N ₂ O)	I-3
I.2.3 High-GWP Gases.....	I-4
I.2.3.1 HFCs.....	I-4
I.2.3.2 PFCs.....	I-4
I.2.3.3 Sulfur Hexafluoride (SF ₆).....	I-4
I.2.4 Use of GWPs in this Report.....	I-5
I.3 Methodology	I-5
I.3.1 Baseline Emissions for Non-CO ₂ Greenhouse Gases.....	I-6
I.3.1.1 Baseline Emissions for Agriculture	I-7
I.3.1.2 Baseline Emissions for Fluorinated Gases.....	I-7
I.3.2 Mitigation Option Analysis Methodology	I-8
I.3.2.1 Technical Characteristics of Abatement Options	I-9
I.3.2.2 Economic Characteristics of Abatement Options.....	I-11
I.3.3 Marginal Abatement Curves.....	I-13
I.3.4 Methodological Enhancements from Energy Modeling Forum Study	I-15
I.4 Aggregate Results	I-16
I.4.1 Baselines.....	I-16
I.4.1.1 By Non-CO ₂ Greenhouse Gas	I-16
I.4.1.2 By Major Emitting Sectors and Countries	I-17
I.4.2 Global MACs.....	I-19
I.5 Limitations and Applications of MACs.....	I-21
I.5.1 Limitations and Uncertainties.....	I-21
I.5.1.1 Exclusion of Transaction Costs	I-22
I.5.1.2 Static Approach to Abatement Assessment	I-22
I.5.1.3 Limited Use of Regional Data	I-22
I.5.1.4 Exclusion of Indirect Emissions Reductions	I-22

Section	Page
I.5.2 Practical Applications of MACs in Economic Models.....	I-22
I.6 References	I-23
Appendix	
A: Additional Information to Technical Summary	A-1
II. Energy	
II.1 Coal Mining Sector	II-1
II.1.1 Introduction.....	II-1
II.1.2 Baseline Emissions Estimates.....	II-2
II.1.2.1 Activity Data.....	II-3
II.1.2.2 Emissions Factors and Related Assumptions	II-4
II.1.2.3 Emissions Estimates and Related Assumptions	II-5
II.1.3 Cost of CH ₄ Emissions Reductions from Coal Mining.....	II-6
II.1.3.1 Abatement Option Opportunities	II-6
II.1.4 Results	II-9
II.1.4.1 Data Tables and Graphs.....	II-9
II.1.4.2 Uncertainties and Limitations	II-11
II.1.5 Summary.....	II-12
II.1.6 References	II-12
II.2 Natural Gas Sector	II-15
II.2.1 Introduction.....	II-15
II.2.2 Baseline Emissions Estimates.....	II-17
II.2.2.1 Activity Data.....	II-17
II.2.2.2 Emissions Factors and Related Assumptions	II-19
II.2.2.3 Emissions Estimates and Related Assumptions	II-22
II.2.3 Cost of CH ₄ Emissions Reductions from Natural Gas Systems	II-23
II.2.3.1 Abatement Option Opportunities	II-24
II.2.4 Results	II-26
II.2.4.1 Data Tables and Graphs.....	II-26
II.2.5 Summary.....	II-30
II.2.6 References	II-30
II.3 Oil Sector	II-31
II.3.1 Introduction.....	II-31

Section	Page
---------	------

II.3.1.1	Emissions from Production Field Operations.....	II-32
II.3.1.2	Emissions from Crude Oil Transportation.....	II-32
II.3.1.3	Emissions from Crude Oil Refining	II-32
II.3.1.4	Abatement Options.....	II-32
II.3.2	Baseline Emissions Estimates.....	II-33
II.3.2.1	Activity Factors	II-33
II.3.2.2	Emissions Factors and Related Assumptions	II-33
II.3.2.3	Emissions Estimates and Related Assumptions	II-37
II.3.3	The Cost of CH ₄ Emissions Reductions from Oil.....	II-37
II.3.3.1	Abatement Option Opportunities	II-37
II.3.4	Results	II-40
II.3.4.1	Data Tables and Graphs.....	II-40
II.3.5	Uncertainties and Limitations.....	II-40
II.3.6	Summary.....	II-42
II.3.7	References.....	II-42

Appendixes

B:	Coal Mining Sector--Incorporating Technology Change to MAC Analysis.....	B-1
C:	Natural Gas Sector--Incorporating Technology Change to MAC Analysis.....	C-1
D:	Supporting Materials for Analysis of Oil Systems.....	D-1

III. Waste

III.1	Landfill Sector	III-1
III.1.1	Introduction.....	III-1
III.1.2	Baseline Emissions Estimates.....	III-2
III.1.2.1	Activity Data.....	III-3
III.1.2.2	Emissions Factors and Related Assumptions	III-3
III.1.2.3	Emissions Estimates and Related Assumptions	III-4
III.1.3	Cost of Emissions Reductions from Landfills.....	III-7
III.1.3.1	Abatement Option Opportunities	III-7
III.1.4	Results	III-9
III.1.4.1	Data Tables and Graphs.....	III-9
III.1.4.2	Uncertainties and Limitations.....	III-11
III.1.5	Summary and Analysis.....	III-12
III.1.6	References.....	III-12

Section	Page
III.2 Wastewater Sector.....	III-13
III.2.1 Introduction.....	III-13
III.2.1.1 Emissions from Wastewater Systems.....	III-14
III.2.2 Baseline Emissions Estimates.....	III-16
III.2.2.1 Activity Factors	III-17
III.2.2.2 Emissions Factors and Related Assumptions	III-18
III.2.2.3 Emissions Estimates and Related Assumptions.....	III-18
III.2.3 Emissions Reductions from Wastewater	III-20
III.2.3.1 Abatement Option Opportunities	III-20
III.2.3.2 Uncertainties and Limitations.....	III-22
III.2.4 Summary.....	III-22
III.2.5 References.....	III-22
Appendix	
E: MSW Landfill Sector—Incorporating Technology Change to MAC Analysis.....	E-1
IV. Industrial Processes	
IV.1 N₂O Emissions from Nitric and Adipic Acid Production	IV-1
IV.1.1 Introduction.....	IV-1
IV.1.1.1 Nitric Acid	IV-2
IV.1.1.2 Adipic Acid.....	IV-2
IV.1.2 Baseline Emissions Estimates.....	IV-2
IV.1.2.1 Activity Factors	IV-2
IV.1.2.2 Emissions Factors and Related Assumptions	IV-4
IV.1.2.3 Emissions Estimates and Related Assumptions.....	IV-5
IV.1.3 Cost of N ₂ O Emissions Reductions from Industrial Processes	IV-6
IV.1.3.1 Nitric Acid: N ₂ O Abatement Option Opportunities.....	IV-7
IV.1.3.2 Adipic Acid: N ₂ O Abatement Option Opportunities	IV-8
IV.1.4 Results	IV-8
IV.1.4.1 Data Tables and Graphs.....	IV-8
IV.1.4.2 Uncertainties and Limitations.....	IV-8
IV.1.5 Summary.....	IV-12
IV.1.6 References.....	IV-12

Section	Page
IV.2 HFC Emissions from Refrigeration and Air-Conditioning.....	IV-15
IV.2.1 Introduction.....	IV-15
IV.2.1.1 Household Refrigeration	IV-15
IV.2.1.2 Motor Vehicle Air-Conditioning (MVAC)	IV-16
IV.2.1.3 Chillers	IV-16
IV.2.1.4 Retail Food Refrigeration.....	IV-17
IV.2.1.5 Cold Storage Warehouses.....	IV-17
IV.2.1.6 Refrigerated Transport.....	IV-17
IV.2.1.7 Industrial Process Refrigeration	IV-18
IV.2.1.8 Residential and Small Commercial Air-Conditioning and Heat Pumps	IV-18
IV.2.2 Baseline Emissions Estimates.....	IV-18
IV.2.2.1 Emissions Estimating Methodology.....	IV-18
IV.2.2.2 Baseline Emissions.....	IV-24
IV.2.3 Cost of HFC Emissions Reduction from Refrigeration and Air-Conditioning	IV-25
IV.2.3.1 Description and Cost Analysis of Abatement Options.....	IV-25
IV.2.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options	IV-45
IV.2.4 Results	IV-45
IV.2.4.1 Data Tables and Graphs.....	IV-46
IV.2.4.2 Uncertainties and Limitations.....	IV-54
IV.2.5 Summary.....	IV-54
IV.2.6 References.....	IV-55
IV.3 HFC, HFE, and PFC Emissions from Solvents	IV-59
IV.3.1 Introduction.....	IV-59
IV.3.2 Baseline Emissions Estimates.....	IV-60
IV.3.2.1 Emissions Estimating Methodology.....	IV-60
IV.3.2.2 Baseline Emissions.....	IV-61
IV.3.3 Cost of HFC, HFE, and PFC Emissions Reductions for Solvents.....	IV-62
IV.3.3.1 Description and Cost Analysis of Abatement Options.....	IV-62
IV.3.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options	IV-67
IV.3.4 Results	IV-68
IV.3.4.1 Data Tables and Graphs.....	IV-68
IV.3.4.2 Uncertainties and Limitations.....	IV-71

Section	Page
IV.3.5 Summary.....	IV-71
IV.3.6 References.....	IV-72
IV.4 HFC Emissions from Foams.....	IV-75
IV.4.1 Introduction.....	IV-75
IV.4.2 Baseline Emissions Estimates.....	IV-76
IV.4.2.1 Emissions Estimating Methodology.....	IV-76
IV.4.2.2 Baseline Emissions.....	IV-79
IV.4.3 Cost of HFC Emissions Reductions from Foams.....	IV-81
IV.4.3.1 Abatement Options	IV-81
IV.4.3.2 Description and Costs of Abatement Options	IV-83
IV.4.3.3 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options	IV-90
IV.4.4 Results	IV-91
IV.4.4.1 Data Tables and Graphs.....	IV-91
IV.4.4.2 Uncertainties and Limitations.....	IV-91
IV.4.5 Summary.....	IV-99
IV.4.6 References.....	IV-100
IV.5 HFC Emissions from Aerosols.....	IV-103
IV.5.1 Introduction.....	IV-103
IV.5.2 Baseline Emissions Estimates.....	IV-103
IV.5.2.1 Emissions Estimating Methodology.....	IV-103
IV.5.2.2 Baseline Emissions.....	IV-105
IV.5.3 Cost of HFC Emissions Reductions for Aerosols	IV-105
IV.5.3.1 Description and Cost Analysis of Abatement Options.....	IV-105
IV.5.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options	IV-110
IV.5.4 Results	IV-111
IV.5.4.1 Data Tables and Graphs.....	IV-111
IV.5.4.2 Uncertainties and Limitations.....	IV-116
IV.5.5 Summary.....	IV-116
IV.5.5.1 MDI Aerosols	IV-117
IV.5.5.2 Non-MDI Aerosols	IV-117
IV.5.6 References.....	IV-117

Section	Page
IV.6 HFC Emissions from Fire Extinguishing.....	IV-119
IV.6.1 Introduction.....	IV-119
IV.6.2 Baseline Emissions Estimates.....	IV-121
IV.6.2.1 Emissions Estimating Methodology.....	IV-121
IV.6.2.2 Baseline Emissions.....	IV-122
IV.6.3 Cost of HFC Emissions Reductions from Fire Extinguishing.....	IV-124
IV.6.3.1 Description and Cost Analysis of Abatement Options.....	IV-124
IV.6.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options	IV-130
IV.6.4 Results	IV-133
IV.6.4.1 Data Tables and Graphs.....	IV-133
IV.6.4.2 Uncertainties and Limitations.....	IV-136
IV.6.5 Summary.....	IV-136
IV.6.6 References.....	IV-136
IV.7 PFC Emissions from Aluminum Production.....	IV-139
IV.7.1 Technology-Adoption Baseline	IV-139
IV.7.2 No-Action Baseline.....	IV-141
IV.7.3 Cost of PFC Emissions Reduction from Aluminum Production.....	IV-142
IV.7.3.1 Abatement Options	IV-142
IV.7.4 Results	IV-146
IV.7.4.1 Data Tables and Graphs.....	IV-146
IV.7.4.2 Global and Regional MACs and Analysis.....	IV-149
IV.7.4.3 Uncertainties and Limitations.....	IV-151
IV.7.5 References.....	IV-152
IV.8 HFC-23 Emissions from HCFC-22 Production.....	IV-155
IV.8.1 Source Description.....	IV-155
IV.8.1.2 No-Action Baseline.....	IV-156
IV.8.1.3 Technology-Adoption Baseline.....	IV-158
IV.8.2 Cost of HFC-23 Reduction from HCFC-22 Production	IV-159
IV.8.2.1 Abatement Options	IV-159
IV.8.3 Results	IV-162
IV.8.3.1 Data Tables and Graphs.....	IV-162
IV.8.3.2 Global and Regional MACs and Analysis.....	IV-165
IV.8.3.3 Uncertainties and Limitations.....	IV-167

Section	Page
IV.8.4 References.....	IV-168
IV.9 PFC and SF₆ Emissions from Semiconductor Manufacturing.....	IV-169
IV.9.1 Source Description.....	IV-169
IV.9.1.1 Technology-Adoption Baseline.....	IV-170
IV.9.1.2 No-Action Baseline.....	IV-172
IV.9.2 Cost of PFC and SF ₆ Emissions Reduction from Semiconductor Manufacturing	IV-173
IV.9.2.1 Abatement Options	IV-173
IV.9.3 Results	IV-179
IV.9.3.1 Data Tables and Graphs.....	IV-179
IV.9.3.2 Global and Regional MACs and Analysis.....	IV-179
IV.9.3.3 Uncertainties and Limitations.....	IV-183
IV.9.4 References.....	IV-185
IV.10 SF₆ Emissions from Electric Power Systems.....	IV-187
IV.10.1 Source Description.....	IV-187
IV.10.1.1 Technology-Adoption Baseline.....	IV-188
IV.10.1.2 No-Action Baseline.....	IV-189
IV.10.2 Cost of SF ₆ Emissions Reduction from Electric Power Systems.....	IV-190
IV.10.2.1 Abatement Options	IV-190
IV.10.3 Results	IV-195
IV.10.3.1 Data Tables and Graphs.....	IV-195
IV.10.3.2 Global and Regional MACs and Analysis.....	IV-198
IV.10.3.3 Uncertainties and Limitations.....	IV-199
IV.10.4 References.....	IV-202
IV.11 SF₆ Emissions from Magnesium (Mg) Production	IV-205
IV.11.1 Source Description.....	IV-205
IV.11.1.1 Technology-Adoption Baseline.....	IV-205
IV.11.1.2 No-Action Baseline.....	IV-207
IV.11.2 Cost of SF ₆ Emissions Reduction from Mg Production and Processing Operations.....	IV-208
IV.11.2.1 Abatement Options	IV-208
IV.11.3 Results	IV-210
IV.11.3.1 Data Tables and Graphs.....	IV-210
IV.11.3.2 Global and Regional MACs and Analysis.....	IV-213
IV.11.3.3 Uncertainties and Limitations.....	IV-215
IV.11.4 References.....	IV-216

Appendixes:

F:	Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Refrigeration and Air-Conditioning	F-1
G:	Cost and Emissions Reduction Analysis for Options to Abate International HFC, HFE, and PFC Emissions from Solvents.....	G-1
H:	Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Foams	H-1
I:	Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Aerosols	I-1
J:	Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Fire Extinguishing	J-1
K:	Cost and Emissions Reduction Analysis for Options in Aluminum Production	K-1
L:	Cost and Emissions Reduction Analysis for Options in HCFC-22 Production.....	L-1
M:	Cost and Emissions Reduction Analysis for Options in Semiconductor Manufacturing	M-1
N:	Cost and Emissions Reduction Analysis for Options in Electric Power Systems.....	N-1
O:	Cost and Emissions Reduction Analysis for Options in Magnesium Production	O-1

V. Agriculture

V.1	Introduction and Background	V-1
V.1.1	Brief Points of Comparison with Other Non-CO ₂ Emissions Sectors	V-2
V.1.2	Previous Estimates for EMF-21 and New Improvements.....	V-2
V.2	Emissions Characterization, Baselines, and Mitigation Scenarios.....	V-5
V.2.1	Croplands (N ₂ O and Soil Carbon).....	V-5
V.2.1.1	Cropland N ₂ O and Soil Carbon Emissions Characterization	V-5
V.2.1.2	DAYCENT Baseline Estimates of Cropland N ₂ O, Soil Carbon, and Yields.....	V-6
V.2.1.3	Mitigation Options for Cropland N ₂ O and Soil Carbon Emissions.....	V-8
V.2.1.4	DAYCENT Results for Changes in Cropland N ₂ O, Soil Carbon, and Yields	V-10
V.2.2	Rice (CH ₄ , N ₂ O, and Soil Carbon)	V-12
V.2.2.1	Rice CH ₄ , N ₂ O, and Carbon Emissions Characterization.....	V-12
V.2.2.2	DNDC Baseline Estimates of Rice CH ₄ , N ₂ O, Soil Carbon, and Yields.....	V-13
V.2.2.3	Mitigation Options for Rice CH ₄ , N ₂ O, and Soil Carbon Emissions.....	V-16
V.2.2.4	DNDC Estimates for Changes in Rice CH ₄ , N ₂ O, Soil Carbon, and Yields	V-17
V.2.3	Livestock (CH ₄ and N ₂ O)	V-20
V.2.3.1	Livestock Enteric CH ₄ Emissions Characterization	V-20

V.2.3.2	Livestock Manure CH ₄ and N ₂ O Emissions Characterization	V-20
V.2.3.3	The USEPA Baseline Estimates of Livestock Enteric CH ₄ Emissions	V-21
V.2.3.4	The USEPA Baseline Estimates of Livestock Manure CH ₄ and N ₂ O Emissions	V-21
V.2.3.5	Mitigation Options for Livestock Emissions	V-21
V.2.3.6	Changes in Livestock CH ₄ and Productivity	V-26
V.3	Results	V-31
V.3.1	Estimating Average Costs and Constructing Abatement Curves	V-31
V.3.2	Baselines, Mitigation Costs and MACs for Croplands	V-32
V.3.3	Baselines, Mitigation Costs, and MACs for Rice Cultivation	V-41
V.3.4	Baselines, Mitigation Costs, and MACs for Livestock Management	V-45
V.3.5	Baselines, Mitigation Costs, and MACs for Total Agriculture	V-55
V.3.6	Agricultural Commodity Market Impacts of Adopting Mitigation Options: Use of the IMPACT Model	V-57
V.4	Conclusions	V-65
V.5	References	V-69
Appendixes:		
P:	Summary of Non-CO ₂ Agricultural Mitigation Analysis Completed for EMF-21	P-1
Q:	DAYCENT Model Description and Methods	Q-1
R:	DNDC Model Description and Methods	R-1
S:	Baseline Differences and Methods for This Mitigation Analysis	S-1
T:	IMPACT Commodity Price Data	T-1
U:	Detailed Data Tables	U-1

List of Figures

Number

Page

Section I

2-1	Contribution of Anthropogenic Emissions of Greenhouse Gases to the Enhanced Greenhouse Effect from Preindustrial to Present (measured in watts/meter ²)	I-2
3-1	Illustrative Non-CO ₂ Marginal Abatement Curve	I-13
4-1	Percentage Share of Global Non-CO ₂ Emissions by Type of Gas in 2005.....	I-16
4-2	Non-CO ₂ Global Emissions Forecast to 2020 by Greenhouse Gas	I-17
4-3	Global Emissions by Major Sector for All Non-CO ₂ Greenhouse Gases.....	I-18
4-4	Projected World Emissions Baselines for Non-CO ₂ Greenhouse Gases, Including the Top Emitting Regions.....	I-18
4-5	Global 2020 MACs for Non-CO ₂ Greenhouse Gases by Major Sector.....	I-19
4-6	Global 2020 MACs by Non-CO ₂ Greenhouse Gas Type.....	I-20
4-7	Global 2020 MACs for Non-CO ₂ Greenhouse Gases by Major Emitting Regions	I-20

Section II

1-1	CH ₄ Emissions from Coal Mining, by Country: 2000–2020	II-1
1-2	EMF MACs for Top Five Emitting Countries/Regions from Coal: 2020	II-11
2-1	CH ₄ from Natural Gas Systems by Country: 2000–2020	II-15
2-2	EMF MACs for Top Five Emitting Countries/Regions from Natural Gas: 2020	II-29
3-1	CH ₄ Emissions from Oil Production by Country: 2000–2020	II-31
3-2	EMF MACs for Top Five Emitting Countries/Regions from Oil: 2020.....	II-42

Section III

1-1	CH ₄ Emissions from Municipal Solid Waste by Country: 2000–2020	III-1
1-2	Components of CH ₄ Emissions from Landfills.....	III-5
1-3	EMF MACs for Top Five Emitting Countries/Regions from Landfills: 2020.....	III-11
2-1	CH ₄ Emissions from Wastewater by Country: 2000–2020	III-13
2-2	N ₂ O Emissions from Wastewater by Country: 2000–2020	III-14

Section IV

1-1	N ₂ O Emissions from Industrial Production by Country: 2000–2020	IV-1
1-2	EMF MACs for Top Five Emitting Country/Regions from Nitric Acid Production: 2020.....	IV-11
1-3	EMF MACs for Top Five Emitting Country/Regions from Adipic Acid Production: 2020....	IV-11
2-1	Baseline HFC Emissions from Refrigeration and Air-Conditioning by Region (MtCO ₂ eq).....	IV-27
2-2	2010 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate	IV-53
2-3	2020 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate	IV-54
3-1	Total Baseline HFC, PFC, and HFE Emissions Estimates from Solvents (MtCO ₂ eq)	IV-63

<u>Number</u>		<u>Page</u>
3-2	2010 MAC for Solvents, 10% Discount Rate, 40% Tax Rate	IV-70
3-3	2020 MAC for Solvents, 10% Discount Rate, 40% Tax Rate	IV-71
4-1	Total Baseline Emissions Estimates for Foams (MtCO ₂ eq)	IV-80
4-2	2010 MAC for Foams, 10% Discount Rate, 40% Tax Rate	IV-99
4-3	2020 MAC for Foams, 10% Discount Rate, 40% Tax Rate	IV-99
5-1	Total Baseline HFC Emissions Estimates from MDI Aerosols (MtCO ₂ eq)	IV-106
5-2	Total Baseline HFC Emissions Estimates from Non-MDI Aerosols (MtCO ₂ eq)	IV-107
5-3	2010 MAC for MDI Aerosols, 10% Discount Rate, 40% Tax Rate	IV-114
5-4	2020 MAC for MDI Aerosols, 10% Discount Rate, 40% Tax Rate	IV-115
5-5	2010 MAC for Non-MDI Aerosols, 10% Discount Rate, 40% Tax Rate	IV-115
5-6	2020 MAC for Non-MDI Aerosols, 10% Discount Rate, 40% Tax Rate	IV-116
6-1	Baseline HFC Emissions from Fire Extinguishing by Region (MtCO ₂ eq).....	IV-123
6-2	2010 MAC for Fire Extinguishing, 10% Discount Rate, 40% Tax Rate	IV-135
6-3	2020 MAC for Fire Extinguishing, 10% Discount Rate, 40% Tax Rate	IV-135
7-1	PFC Emissions from Aluminum Production Based on a Technology-Adoption Scenario—1990–2020 (MtCO ₂ eq)	IV-141
7-2	PFC Emissions from Aluminum Production Based on a No-Action Scenario—1990– 2020 (MtCO ₂ eq)	IV-142
7-3	2010 and 2020 Global Technology-Adoption and No-Action MACs for Primary Aluminum Production.....	IV-150
7-4	2010 Regional Technology-Adoption MACs for Primary Aluminum Production.....	IV-150
7-5	2020 Regional Technology-Adoption MACs for Primary Aluminum Production.....	IV-151
8-1	HFC-23 Emissions from HCFC-22 Production Based on a No-Action Scenario—1990– 2020 (MtCO ₂ eq)	IV-157
8-2	HFC-23 Emissions from HCFC-22 Production Based on a Technology-Adoption Scenario—1990–2020 (MtCO ₂ eq)	IV-158
8-3	2010 and 2020 Global Technology-Adoption and No-Action MACs for HCFC-22 Production	IV-165
8-4	2010 Regional Technology-Adoption MACs	IV-166
8-5	2020 Regional Technology-Adoption MACs	IV-166
9-1	PFC Emissions from Semiconductor Manufacturing Based on a Technology-Adoption Scenario—1990 through 2020 (MtCO ₂ eq).....	IV-171
9-2	WSC and Non-WSC Countries' Contribution to Global PFC Emissions (MtCO ₂ eq).....	IV-171
9-3	PFC Emissions from Semiconductor Manufacturing Based on a No-Action Scenario— 1990 through 2020 (MtCO ₂ eq).....	IV-173
9-4	2010 Regional Technology-Adoption MACs for Semiconductor Manufacturing	IV-184
9-5	2020 Regional Technology-Adoption MACs for Semiconductor Manufacturing	IV-184
10-1	SF ₆ Emissions from Electric Power Systems on a Technology-Adoption Scenario— 1990–2020 (MtCO ₂ eq)	IV-189
10-2	SF ₆ Emissions from Electric Power Systems on a No-Action Scenario—1990–2020 (MtCO ₂ eq).....	IV-190
10-3	2010 and 2020 Global Technology-Adoption and No-Action MACs for Electric Power Systems.....	IV-198
10-4	2010 Regional Technology-Adoption MACs for Electric Power Systems.....	IV-200

<u>Number</u>		<u>Page</u>
10-5	2020 Regional Technology-Adoption MACs for Electric Power Systems.....	IV-200
11-1	SF ₆ Emissions from Mg Manufacturing Based on a Technology-Adoption Scenario— 1990–2020 (MtCO ₂ eq).....	IV-207
11-2	SF ₆ Emissions from Mg Manufacturing Based on a No-Action Scenario—1990–2020 (MtCO ₂ eq).....	IV-208
11-3	2010 and 2020 Global Technology-Adoption and No-Action MACs for Mg Production.....	IV-213
11-4	2010 Regional Technology-Adoption MACs	IV-214
11-5	2020 Regional Technology-Adoption MACs	IV-214

Section V

1-1	Global Cropland Yields for Baseline and Mitigation Options Estimated by DAYCENT, 2010	V-10
1-2	Global Net Greenhouse Gas (N ₂ O and Soil Carbon) Cropland Emissions Estimated by DAYCENT under Baseline and Mitigation Scenarios	V-11
1-3	Global Net Greenhouse Gas (CH ₄ and N ₂ O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Number of Animals Constant.....	V-26
1-4	Global Net Greenhouse Gas (CH ₄ and N ₂ O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Production Constant.....	V-27
1-5	Global Beef Production under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant.....	V-28
1-6	Global Production of Milk from Dairy Cattle under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant	V-28
1-7	Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, 2000–2020	V-37
1-8	Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, Allocating Adoption of Mitigation Strategies to the Three Most Effective Options Only, 2000–2020	V-38
1-9	MAC for Net Greenhouse Gas Emissions from Cropland Management in the United States, Holding Area Constant, 2000–2020	V-39
1-10	MAC for Net Greenhouse Gas Emissions from Cropland Management in the EU-15, Holding Area Constant, 2000–2020	V-39
1-11	MAC for Net Greenhouse Gas Emissions from Cropland Management in the FSU, Holding Area Constant, 2000–2020	V-40
1-12	MAC for Net Greenhouse Gas Emissions from Cropland Management in China, Holding Area Constant, 2000–2020	V-40
1-13	Global MAC for Net Greenhouse Gas Emissions from Rice Cultivation, Holding Area Constant, 2000–2020	V-43
1-14	MAC for Net Greenhouse Gas Emissions from Rice Cultivation in India, Holding Area Constant, 2000–2020	V-44
1-15	MAC for Net Greenhouse Gas Emissions from Rice Cultivation in China, Holding Area Constant, 2000–2020	V-44

<u>Number</u>	<u>Page</u>
1-16 Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Number of Animals Constant, 2000–2020	V-50
1-17 Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Production Constant, 2000–2020	V-50
1-18 MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Number of Animals Constant, 2000–2020	V-51
1-19 MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Number of Animals Constant, 2000–2020	V-51
1-20 MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Number of Animals Constant, 2000–2020	V-52
1-21 MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Number of Animals Constant, 2000–2020	V-52
1-22 MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Production Constant, 2000–2020	V-53
1-23 MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Production Constant, 2000–2020	V-53
1-24 MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Production Constant, 2000–2020	V-54
1-25 MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Production Constant, 2000–2020	V-54
1-26 Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Area/Animals Constant, 2000–2020	V-56
1-27 Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Production Constant, 2000–2020	V-57
1-28 Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on World Prices Using the IMPACT Model	V-58
1-29 Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Production Using the IMPACT Model	V-59
1-30 Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Number of Animals Using the IMPACT Model	V-59
1-31 Effect of Global Adoption of the Shallow Flooding Mitigation Option on World Prices Using the IMPACT Model	V-61
1-32 Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Production Using the IMPACT Model	V-61
1-33 Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Rice Area Using the IMPACT Model	V-62
1-34 Net GHG Abatement under Global Adoption of the Antimethanogen Vaccine Option with Number of Cattle Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010	V-62
1-35 Comparison of Net GHG Abatement from Rice Cultivation under Global Adoption of the Shallow Flooding Mitigation Option with Area Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010	V-63

List of Tables

Number

Page

Section I

2-1	Global Greenhouse Gas (GHG) Emissions for 2000 (MtCO ₂ eq).....	I-2
2-2	Global Warming Potentials	I-5
3-1	Abatement Potential Calculation for Mitigation Options	I-10
3-2	Financial Assumptions in Breakeven Price Calculations for Abatement Options.....	I-13

Section II

1-1	Historical Coal Mining Activity Data for Selected Countries (Million Metric Tons).....	II-4
1-2	IPCC Suggested Underground Emissions Factors for Selected Countries	II-5
1-3	Historical Baseline Emissions for Coal Mine CH ₄ for Selected Countries (MtCO ₂ eq)	II-5
1-4	Projected Baseline Emissions for Coal Mine CH ₄ for Selected Countries (MtCO ₂ eq).....	II-6
1-5	Summary of Average Abatement Costs and Benefits for U.S. Coal Mines (in 2000\$).....	II-7
1-6	Summary of Coal Mining Abatement Options Included in the Analysis.....	II-9
1-7	Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO ₂ eq)	II-10
1-8	Coal Mining MACs for Countries Included in the Analysis.....	II-10
2-1	Natural Gas Industry Characterization	II-16
2-2	Natural Gas Production by Country and Region: 1980–2003 (Trillion Cubic Feet).....	II-18
2-3	Natural Gas Consumption by Country and Region: 1980–2003 (Trillion Cubic Feet)	II-19
2-4	Projected Natural Gas Production by Country and Region: 2010–2025 (Trillion Cubic Feet)	II-20
2-5	Projected Natural Gas Consumption by Country and Region: 2010–2025 (Trillion Cubic Feet)	II-20
2-6	IPCC Estimated Emissions Factors from Natural Gas by Region	II-21
2-7	Baseline Emissions for Natural Gas Systems for Selected Countries: 1990–2000 (MtCO ₂ eq).....	II-21
2-8	Projected Baseline Emissions for Natural Gas Systems for Selected Countries: 2005–2020 (MtCO ₂ eq)	II-23
2-9	Prevalence of Abatement Options by Infrastructure Component	II-23
2-10	Natural Gas MACs for Countries Included in the Analysis	II-27
2-11	Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO ₂ eq)	II-28
2-12	Natural Gas MACs for Countries Included in the Analysis	II-29
3-1	Oil Production by Country: 1990–2003 (MMbbl per Day)	II-34
3-2	Forecasted Oil Production for Selected Countries (MMbbl per Day, Unless Otherwise Noted).....	II-35
3-3	Forecasted Oil Consumption for Selected Countries (MMbbl per Day, Unless Otherwise Noted)	II-36
3-4	IPCC Emissions Factors for Petroleum Systems in Select Regions	II-37
3-5	Baseline Emissions from Oil Production, by Country: 1990–2000 (MtCO ₂ eq)	II-38
3-6	Projected Baseline Emissions from Oil Production by Country: 2005–2020 (MtCO ₂ eq).....	II-38
3-7	Cost of Reducing CH ₄ Emissions from Oil.....	II-39

<u>Number</u>		<u>Page</u>
3-8	Percentage Abatement for CH ₄ for Selected Breakeven Price (\$/tCO ₂ eq): 2000.....	II-40
3-9	Baseline Emissions by EMF Regional Grouping: 2000-2020 (MtCO ₂ eq)	II-41
3-10	Oil System MACs for Countries Included in the Analysis	II-41

Section III

1-1	CH ₄ Emissions from Municipal Solid Waste by Country: 1990–2000 (MtCO ₂ eq)	III-5
1-2	Projected Baseline CH ₄ Emissions from Municipal Solid Waste by Country: 2005–2020 (MtCO ₂ eq)	III-6
1-3	Components of Collection and Flaring and LFG Utilization Abatement Options	III-7
1-4	Breakeven Prices of MSW Landfill Technology Options	III-9
1-5	Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO ₂ eq)	III-10
1-6	MSW Landfill MACs for Countries Included in the Analysis.....	III-10
2-1	CH ₄ Emissions from Wastewater by Country: 1990–2000 (MtCO ₂ eq)	III-19
2-2	N ₂ O Emissions from Wastewater by Country: 1990–2000 (MtCO ₂ eq)	III-19
2-3	Projected Baseline CH ₄ Emissions from Wastewater by Country: 2005–2020 (MtCO ₂ eq)	III-21
2-4	Projected Baseline N ₂ O Emissions from Wastewater by Country: 2005–2020 (MtCO ₂ eq)	III-21

Section IV

1-1	2003 Adipic Acid Production Capacity (Thousands of Metric Tons/Year).....	IV-3
1-2	IPCC Emissions Factors for Nitric Acid Production in Select Countries	IV-4
1-3	N ₂ O Emissions from Nitric and Adipic Acid Production: 1990–2000 (MtCO ₂ eq)	IV-5
1-4	Projected N ₂ O Baseline Emissions from Nitric and Adipic Acid Production: 2005–2020 (MtCO ₂ eq)	IV-6
1-5	Cost of Reducing N ₂ O Emissions from Industrial Processes.....	IV-7
1-6	Projected N ₂ O Emissions from Nitric Acid by Region: 2000–2020 (MtCO ₂ eq)	IV-9
1-7	Percentage Abatement for Nitric Acid for Selected Breakeven Prices (\$/tCO ₂ eq): 2010– 2020	IV-9
1-8	Projected N ₂ O Emissions from Adipic Acid by Region: 2000–2020 (MtCO ₂ eq)	IV-10
1-9	Percentage Abatement for Adipic Acid for Selected Breakeven Prices (\$/tCO ₂ eq): 2010– 2020	IV-10
2-1	Reductions in Baseline Emissions in Non-U.S. Countries to Reflect Market Adjustments	IV-21
2-2	Estimated Percentage of GWP-Weighted Refrigeration and Air-Conditioning HFC Emissions Attributable to MVACs in the United States	IV-22
2-3	Percentage of Newly Manufactured Vehicles Assumed to Have Operational Air- Conditioning Units in India	IV-22
2-4	Percentage of Newly Manufactured Vehicles Assumed to Have Operational Air- Conditioning Units in All Other Countries.....	IV-23
2-5	Estimated Percentage of Refrigeration and Air-Conditioning HFC Emissions Attributable to MVACs.....	IV-24
2-6	Distribution of Refrigeration- and Air-Conditioning–Sector HFC Emissions by End- Use, Region, and Year (Percent)	IV-26
2-7	Total Baseline HFC Emissions from Refrigeration and Air-Conditioning (MtCO ₂ eq)	IV-27
2-8	Assumptions on Duration and Applicability of Emissions Reduction Options	IV-29

<u>Number</u>	<u>Page</u>
2-9	Summary of Assumptions for Leak Repair for Large Equipment IV-32
2-10	Summary of Assumptions for Recovery and Recycling from Small Equipment..... IV-33
2-11	Summary of Assumptions for Distributed Systems for New Stationary Equipment IV-37
2-12	Summary of Assumptions for HFC Secondary Loop Systems for New Stationary Equipment IV-38
2-13	Summary of Assumptions for Ammonia Secondary Loop Systems for New Stationary Equipment IV-39
2-14	Summary of Assumptions for Enhanced HFC-134a Systems for New MVACs..... IV-40
2-15	Summary of Assumptions for HFC-152a DX Systems in New MVACs IV-41
2-16	Summary of Assumptions for CO ₂ Systems in New MVACs IV-43
2-17	Summary of Technical Applicability of Abatement Options by Region (Percent)..... IV-47
2-18	Assumed Regional Market Penetration of Abatement Options into Newly Manufactured Equipment, Expressed as a Percentage of Emissions from New Equipment IV-48
2-19	Market Penetration of Abatement Options, Expressed as a Percentage of Total Sector Emissions IV-49
2-20	Percentage of (Direct) Reduction Off Baseline Emissions of All Abatement Options by Region..... IV-50
2-21	Summary of Abatement Option Cost Assumptions (2000\$)..... IV-51
2-22	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq)..... IV-52
2-23	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq)..... IV-52
2-24	World Breakeven Costs and Emissions Reductions in 2020 for Refrigeration/Air- Conditioning..... IV-53
3-1	General Overview of Solvent Technologies Used Globally IV-60
3-2	Total Baseline HFC, PFC, and HFE Emissions Estimates from Solvents (MtCO ₂ eq) IV-62
3-3	Retrofit Techniques for Batch Vapor Cleaning Machine (Less than 13 Square Feet) IV-65
3-4	Technical Applicability and Incremental Maximum Market Penetration of Solvent Options (Percent) IV-67
3-5	Emissions Reductions Off the Total Solvent Baseline (Percent) IV-68
3-6	Summary of Abatement Option Cost Assumptions IV-68
3-7	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Solvents at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-69
3-8	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Solvents at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-69
3-9	World Breakeven Costs and Emissions Reductions in 2020 for Solvents IV-70
4-1	The USEPA's Vintaging Model Emissions Profile for Foams' End-Uses IV-79
4-2	Baseline Emissions Estimates for Foams (MtCO ₂ eq) IV-80
4-3	Reduction Efficiency of Foam Options (Percent)..... IV-90
4-4	Technical Applicability of Foam Options (Percent)..... IV-92
4-5	Incremental Maximum Market Penetration Expressed as a Percentage of New Emissions for Which the Options Apply IV-93
4-6	Incremental Maximum Market Penetration Expressed as a Percentage of All Emissions IV-94
4-7	Emissions Reductions Off Total Foams Baseline (Percent) IV-95

<u>Number</u>	<u>Page</u>
4-8	Summary of Abatement Option Cost Assumptions IV-96
4-9	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Foams at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-97
4-10	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Foams at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-97
4-11	World Breakeven Costs and Emissions Reductions in 2020 for Foams..... IV-98
5-1	Total Baseline HFC Emissions Estimates from MDI Aerosols (MtCO ₂ eq) IV-106
5-2	Total Baseline HFC Emissions Estimates from Non-MDI Aerosols (MtCO ₂ eq) IV-107
5-3	Technical Applicability and Incremental Maximum Market Penetration of Aerosol Options (Percent) IV-110
5-4	Emissions Reductions Off the Total Applicable Aerosols Baseline (Percent) IV-110
5-5	Summary of Abatement Option Cost Assumptions IV-111
5-6	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-112
5-7	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-112
5-8	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Non-MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-113
5-9	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Non-MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-113
5-10	World Breakeven Costs and Emissions Reductions in 2020 for Aerosols..... IV-114
6-1	Total Baseline HFC Emissions from Fire Extinguishing (MtCO ₂ eq) IV-123
6-2	Assumed Breakout of Total GWP-Weighted Baseline Fire-Extinguishing Emissions (Percent) IV-124
6-3	Summary of Technical Applicability of Abatement Options (Percent)..... IV-130
6-4	Assumed Incremental Market Penetration of Abatement Options into Newly Installed Class A or Class B Extinguishing Systems, Expressed as a Percentage of Emissions from All New Equipment..... IV-131
6-5	Market Penetration of Abatement Options into Newly Installed Class A or Class B Extinguishing Systems, Expressed as a Percentage of Total Sector Emissions IV-132
6-6	Percentage of Emissions Reductions Off Total Fire-Extinguishing Baseline..... IV-132
6-7	Summary of Abatement Option Cost Assumptions (2000\$)..... IV-132
6-8	Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Fire Extinguishing at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-133
6-9	Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Fire Extinguishing at 10% Discount Rate, 40% Tax Rate (\$/tCO ₂ eq) IV-134
6-10	World Breakeven Costs and Emissions Reductions in 2020 for Fire Extinguishing..... IV-134
7-1	Total PFC Emissions from Aluminum Manufacturing (MtCO ₂ eq)—No-Action Baseline ... IV-140
7-2	Total PFC Emissions from Aluminum Manufacturing (MtCO ₂ eq)—Technology-Adoption Baseline..... IV-140
7-3	Reduction Efficiency Potential for Abatement Option by Cell Type (Percent)..... IV-143
7-4	Average Baseline Market Penetration of Complete Retrofits by Cell Type and Scenario (Percent) IV-145

<u>Number</u>	<u>Page</u>
7-5 Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline	IV-146
7-6 Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline	IV-147
7-7 Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline.....	IV-147
7-8 Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline.....	IV-148
7-9 Emissions Reduction and Costs in 2020 — No-Action Baseline	IV-148
7-10 Emissions Reduction and Costs in 2020 — Technology-Adoption Baseline	IV-149
8-1 Total HFC-23 Emissions from HCFC-22 Production (MtCO ₂ eq) — No-Action Baseline	IV-155
8-2 Total HFC-23 Emissions from HCFC-22 Production (MtCO ₂ eq) — Technology-Adoption Baseline.....	IV-156
8-3 Baseline Market Penetration of Thermal Oxidation — No-Action Baseline.....	IV-161
8-4 Baseline Market Penetration of Thermal Oxidation — Technology-Adoption Baseline	IV-161
8-5 Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline.....	IV-162
8-6 Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline.....	IV-163
8-7 Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline.....	IV-163
8-8 Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline.....	IV-164
8-9 World Breakeven Costs and Emissions Reductions in 2020 — No-Action Baseline	IV-164
8-10 World Breakeven Costs and Emissions Reductions in 2020 — Technology-Adoption Baseline.....	IV-164
9-1 Total PFC Emissions from Semiconductor Manufacturing (MtCO ₂ eq) — No-Action Baseline.....	IV-169
9-2 Total PFC Emissions from Semiconductor Manufacturing (MtCO ₂ eq) — Technology- Adoption Baseline.....	IV-170
9-3 Maximum Market Penetrations for WSC Countries in the No-Action Baseline (Percent) ...	IV-174
9-4 Maximum Market Penetrations for Non-WSC Countries in the No-Action Baseline (Percent)	IV-174
9-5 Baseline Market Penetrations for WSC Countries in the Technology-Adoption Baseline (Percent)	IV-175
9-6 Maximum Market Penetrations for WSC Countries in the Technology-Adoption Baseline (Percent).....	IV-175

<u>Number</u>	<u>Page</u>
9-7	Baseline Market Penetrations for Non-WSC Countries in the Technology-Adoption Baseline in 2020 (Percent) IV-175
9-8	Maximum Market Penetrations for Non-WSC Countries in the Technology-Adoption Baseline (Percent)..... IV-176
9-9	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline IV-180
9-10	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline IV-180
9-11	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline IV-181
9-12	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline IV-181
9-13	Emissions Reduction and Costs in 2020 — No-Action Baseline IV-182
9-14	Emissions Reduction and Costs in 2020 — Technology-Adoption Baseline IV-182
10-1	Total SF ₆ Emissions from Electric Power Systems (MtCO ₂ eq) — No-Action Baseline IV-187
10-2	Total SF ₆ Emissions from Electric Power Systems (MtCO ₂ eq) — Technology-Adoption Baseline..... IV-188
10-3	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Electric Power Systems at a 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline..... IV-195
10-4	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline..... IV-196
10-5	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline..... IV-196
10-6	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline..... IV-197
10-7	Emissions Reduction and Costs in 2020 — No-Action Baseline IV-197
10-8	Emissions Reduction and Costs in 2020 — Technology-Adoption Baseline IV-198
11-1	Total SF ₆ Emissions from Mg Manufacturing (MtCO ₂ eq) — No-Action Baseline IV-206
11-2	Total SF ₆ Emissions from Mg Manufacturing (MtCO ₂ eq) — Technology-Adoption Baseline..... IV-206
11-3	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline IV-210
11-4	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — No-Action Baseline IV-211
11-5	Emissions Reductions in 2010 and Breakeven Costs (\$/tCO ₂ eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline IV-211
11-6	Emissions Reductions in 2020 and Breakeven Costs (\$/tCO ₂ eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO ₂ eq) — Technology-Adoption Baseline IV-212
11-7	Emissions Reduction and Costs in 2020 — No-Action Baseline IV-212
11-8	Emissions Reduction and Costs in 2020 — Technology-Adoption Baseline IV-212

Section V

1-1	DAYCENT N ₂ O and Soil Carbon Estimates for 2000, 2010, and 2020 by Key Region (MtCO ₂ eq/yr).....	V-6
1-2	Cropland N ₂ O and Soil Carbon Mitigation Options Run Through DAYCENT	V-9
1-3	Rice-Only Baseline CH ₄ , N ₂ O, and Soil Carbon Estimates for 2000, 2010, and 2020 by Asian Region (Midpoints from DNDC in MtCO ₂ eq/yr; Negative Carbon Numbers Indicate Net Sequestration)	V-15
1-4	Rice CH ₄ , N ₂ O, and Soil Carbon Mitigation Options Run Through DNDC	V-17
1-5	DNDC Estimates of Net Greenhouse Gas Results for Baseline and Mitigation Scenarios for China (Annual Averages in MtCO ₂ eq/yr over 2000–2020)	V-17
1-6	Changes from Baseline in Greenhouse Gas Emissions, Crop Yields, and Water Consumption for China (Annual Averages over 2000–2020; Negative Numbers Indicate Decreases Relative to the Baseline).....	V-18
1-7	Net Greenhouse Gas Results for Baseline and Mitigation Options for Other Asian Countries (Annual Averages in MtCO ₂ eq/yr over 2000–2020).....	V-19
1-8	Livestock Enteric Fermentation Greenhouse Gas Mitigation Options.....	V-23
1-9	Livestock Manure Management Greenhouse Gas Mitigation Options.....	V-25
1-10	Baseline Net GHG Emissions from Croplands from DAYCENT Estimates (MtCO ₂ eq).....	V-33
1-11	Croplands Mitigation Option Detail for Key Regions	V-34
1-12	Croplands: Percentage Reductions from Baselines at Different \$/tCO ₂ eq Prices	V-37
1-13	Baseline Emissions from Rice Cultivation from DNDC Estimates (MtCO ₂ eq).....	V-41
1-14	Rice Cultivation Mitigation Option Detail for Key Regions	V-42
1-15	Rice Cultivation: Percentage Reductions from Baseline at Different \$/tCO ₂ eq Prices	V-43
1-16	Baseline Emissions from Livestock Management from USEPA (2006) (MtCO ₂ eq).....	V-45
1-17	Livestock Mitigation Option Detail for Key Regions.....	V-46
1-18	Livestock Management: Percentage Reductions from Baselines at Different \$/tCO ₂ eq Prices.....	V-49
1-19	Baseline Emissions from All Agriculture Used in This Report (MtCO ₂ eq)	V-55
1-20	Total Agriculture: Percentage Reductions from Baseline at Different \$/tCO ₂ eq Prices	V-56

Executive Summary

The mitigation of noncarbon dioxide (non-CO₂) greenhouse gas emissions can be a relatively inexpensive supplement to CO₂-only mitigation strategies. The non-CO₂ gases include methane (CH₄), nitrous oxide (N₂O), and a number of high global warming potential (high-GWP) or fluorinated gases. These gases trap more heat within the atmosphere than CO₂ per unit weight. Approximately 30 percent of the anthropogenic greenhouse effect since preindustrial times can be attributed to these non-CO₂ greenhouse gases (Intergovernmental Panel for Climate Change [IPCC], 2001b); approximately 24 percent of GWP-weighted greenhouse gas emissions in the year 2000 are comprised of the non-CO₂ greenhouse gases (de la Chesnaye et al., in press; U.S. Environmental Protection Agency [USEPA], 2006).

Given the important role that mitigation of non-CO₂ greenhouse gases can play in climate strategies, there is a clear need for an improved understanding of the mitigation potential for non-CO₂ sources, as well as for the incorporation of non-CO₂ greenhouse gas mitigation in climate economic analyses. This report provides a comprehensive global analysis and resulting data set of marginal abatement curves (MACs) that illustrate the abatement potential of non-CO₂ greenhouse gases by sector and by region. This assessment of mitigation potential is unique because it is comprehensive across all non-CO₂ gases, across all emitting sectors of the economy, and across all regions of the world.

The analysis in this report is the latest refinement of the methodology on mitigation of various non-CO₂ gases, which has been underway since 1999. A significant contribution to the climate change mitigation literature is Stanford University's Energy Modeling Forum Working Group 21 (EMF-21), which focused on mitigation of multiple greenhouse gases and resulted in the publication of a special issue of the *Energy Journal* (see Weyant and de la Chesnaye, in press). The specific non-CO₂ mitigation papers in the EMF-21 study include energy- and industry-related CH₄ and N₂O (Delhotal et al., in press); agricultural-related CH₄ and N₂O (DeAngelo et al., in press); and industry-related fluorinated gases (Ottinger et al., in press). Much of the original work comes from three previous USEPA studies for the United States (2006, 2001, 1999) and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH₄ abatement for European Union (EU) members from 1990 to 2010. These studies provided estimates of potential CH₄ and N₂O emissions reductions from major emitting sectors and quantified costs and benefits of these reductions.

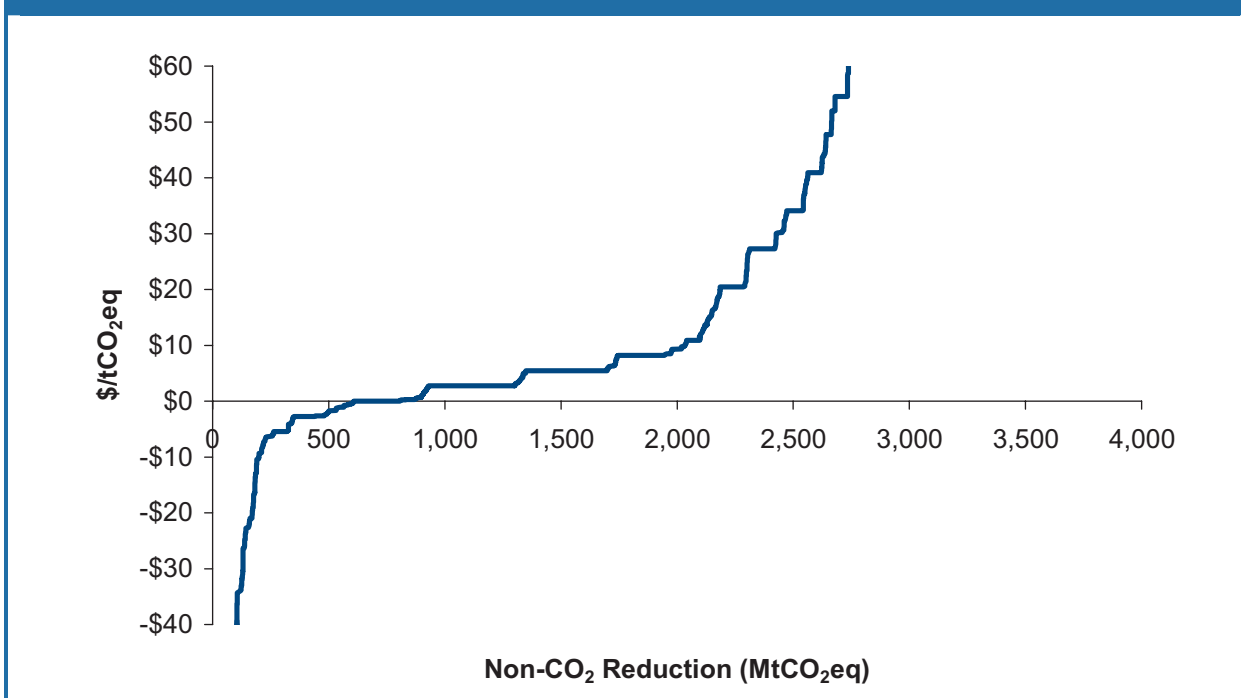
Building on the baseline non-CO₂ emissions projections from the USEPA's *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (2006), this analysis applies mitigation options to the emissions baseline in each sector. Across all the emitting greenhouse gas sectors, for each mitigation option, the technical abatement potential and cost are calculated. The MACs are determined by the series of breakeven price calculations for the suite of available options for each sector and region. Each point along the curve indicates the abatement potential given the economically feasible mitigation technologies at a given breakeven price. This report makes no explicit assumption about policies that would be required to facilitate and generate adoption of mitigation options. Therefore, this report provides estimates of technical mitigation potential.

The result of these efforts is a set of MACs that allow for improved understanding of the mitigation potential for non-CO₂ sources, as well as inclusion of non-CO₂ greenhouse gas mitigation in economic modeling. The MAC data sets can be downloaded in spreadsheet format from the USEPA Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

Highlights of this analysis include the following:

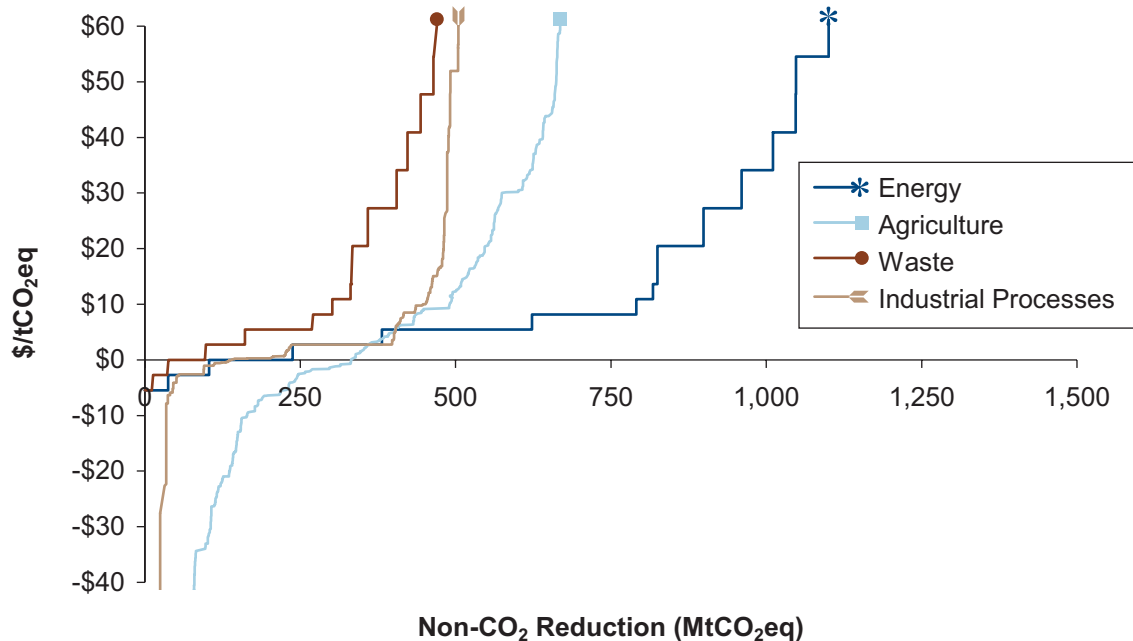
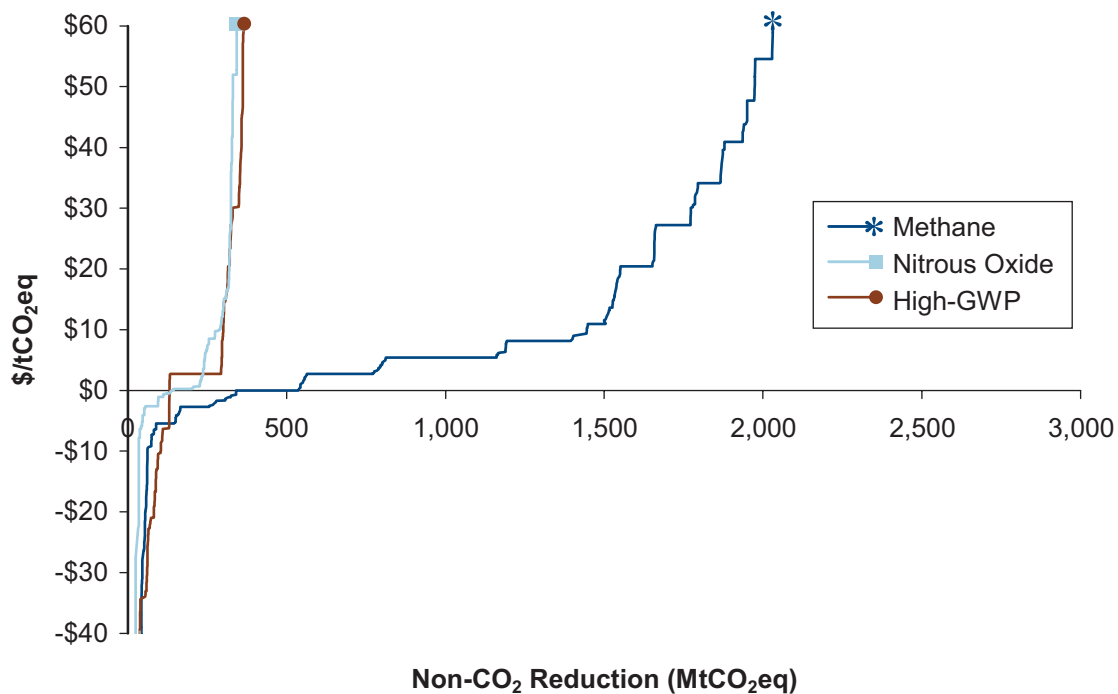
Mitigation of Non-CO₂ Gases Can Play an Important Role in Climate Strategies. Worldwide, the potential for “no-regret” non-CO₂ greenhouse gas abatement is significant. Figure ES-1 shows the global total aggregate MAC for the year 2020. Without a price signal (i.e., at \$0/tCO₂eq), the global mitigation potential is greater than 600 million metric tons of CO₂ equivalent (MtCO₂eq), or 5 percent of the baseline emissions (refer to Section I.3.3 of this report for a more detailed explanation of unrealized mitigation potential in the MACs). As the breakeven price rises, the mitigation potential grows. Significant mitigation opportunities could be realized in the lower range of breakeven prices. The global mitigation potential at a price of \$10/tCO₂eq is greater than 2,000 MtCO₂eq, or 15 percent of the baseline emissions, and greater than 2,185 MtCO₂eq or 17 percent of the baseline emissions at \$20/tCO₂eq. In the higher range of breakeven prices, the MAC becomes steeper, and less mitigation potential exists for each additional increase in price.

Figure ES-1: Global Total Aggregate MAC for Non-CO₂ Greenhouse Gases in 2020



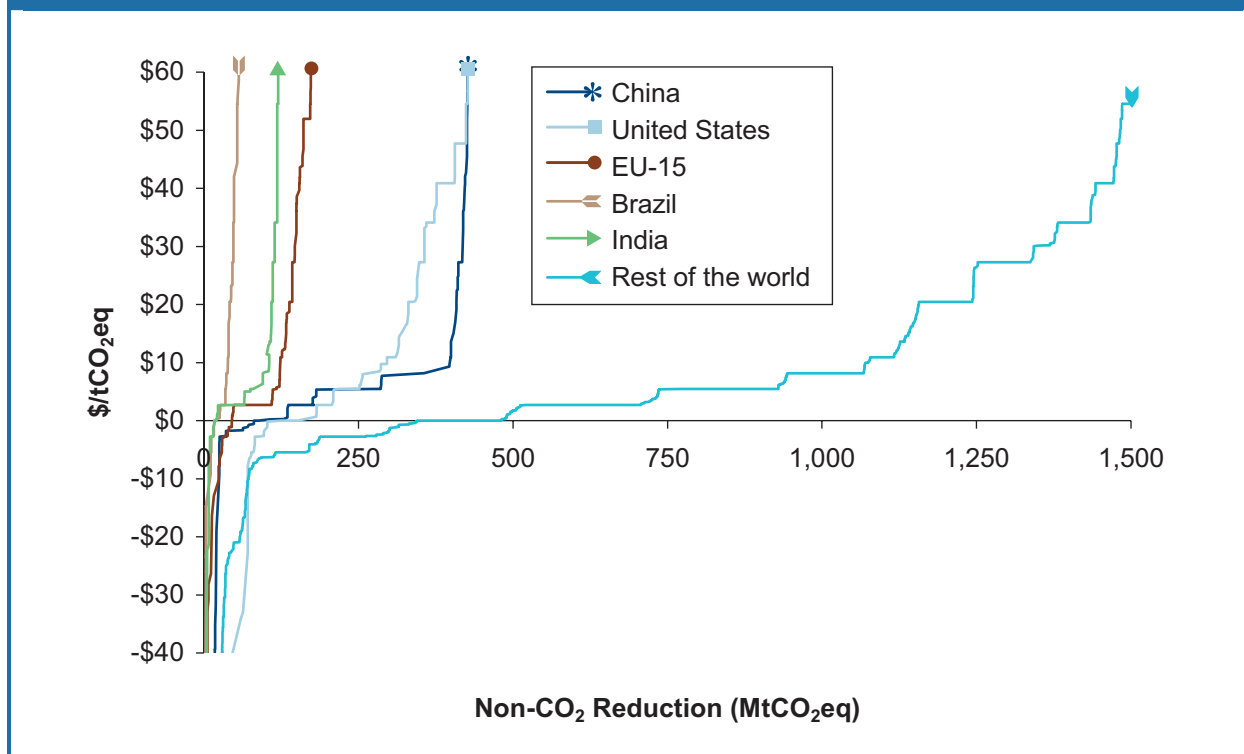
Globally, the Sectors with the Greatest Potential for Mitigation of Non-CO₂ Greenhouse Gases are the Energy and Agriculture Sectors. Figure ES-2 shows the global MACs by economic sector in 2020. At a breakeven price of \$30/tCO₂eq, the potential for reduction of non-CO₂ greenhouse gases is nearly 1,000 MtCO₂eq in the energy sector, and approximately 600 MtCO₂eq in the agriculture sector. While less than that of the energy and agriculture sectors, mitigation potential in the waste and industrial processes sectors can play an important role, particularly in the absence of a carbon price incentive.

Methane Mitigation has the Largest Potential across All the Non-CO₂ Greenhouse Gases. Figure ES-3 shows the global MACs by greenhouse gas type for 2020. At or below \$0/tCO₂eq, the potential for CH₄ mitigation is approximately 500 MtCO₂eq. The potential for reducing CH₄ emissions grows to nearly 1,800 MtCO₂eq as the breakeven price rises from \$0 to \$30/tCO₂eq. While less than that of CH₄, N₂O and high-GWP gases exhibit significant mitigation potential at or below \$0/tCO₂eq.

Figure ES-2: Global 2020 MACs for Non-CO₂ Greenhouse Gases by Major SectorFigure ES-3: Global 2020 MACs by Non-CO₂ Greenhouse Gas Type

Major Emitting Regions of the World Offer Large Potential Mitigation Opportunities. Figure ES-4 shows the global MACs by region for 2020. China, the United States, EU, India, and Brazil are the countries or regions that emit the most non-CO₂ greenhouse gases. As the largest emitters, they also offer important mitigation opportunities. These regions show significant mitigation potential in the lower range of breakeven prices, with the MACs getting steeper in the higher range of breakeven prices as each additional ton of emissions becomes more expensive to reduce.

Figure ES-4: Global 2020 MACs for Non-CO₂ Greenhouse Gases by Major Emitting Regions



The aggregate MACs by economic sector, greenhouse gas type, and region highlight the importance of including non-CO₂ greenhouse gases in the analysis of multigas climate strategies. The MACs illustrate that a significant portion of this emissions reduction potential can be realized at zero or low carbon prices. The mitigation potential in each economic sector is examined in greater detail in this report.

I. Technical Summary

I.1 Overview

The objective of this report is to provide a comprehensive and consistent data set on global mitigation of noncarbon dioxide (non-CO₂) greenhouse gases to facilitate multigas analysis of climate change issues. Mitigating emissions of non-CO₂ greenhouse gases can be relatively inexpensive compared with mitigating CO₂ emissions. Thus, attention has been focused on incorporating international non-CO₂ greenhouse gas mitigation options into climate economic analyses. This requires a large data collection effort and expert analysis of available technologies and opportunities for greenhouse gas reductions across diverse regions and sectors.

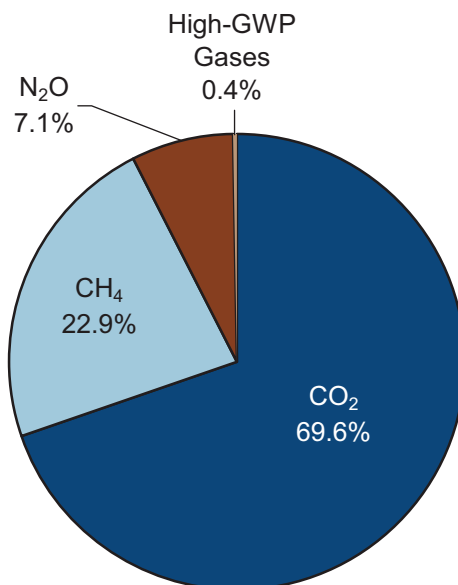
This report builds on a study previously conducted by the U.S. Environmental Protection Agency (USEPA) for the Energy Modeling Forum, Working Group 21 (EMF-21). The Energy Modeling Forum was established by Stanford University to explore energy and environmental issues through the collaboration of diverse modeling teams from around the world. The EMF-21 focused specifically on multigas strategies to address climate change and resulted in the publication of a special issue of the *Energy Journal* (see Weyant and de la Chesnaye [in press]). The specific non-CO₂ mitigation papers in the EMF-21 study include energy- and industry-related methane (CH₄) and nitrous oxide (N₂O) (Delhotal et al., in press), agricultural-related CH₄ and N₂O (DeAngelo et al., in press), and industry-related fluorinated gases (Ottinger et al., in press). Much of the original work comes from two previous USEPA studies for the United States (USEPA, 2001, 1999) and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH₄ abatement for EU members from 1990 to 2010.

Following the basic methodology of the EMF-21 study with some enhancements (as described in Section I.3.4 of this report), this report contains detailed analyses by economic sector and region for all non-CO₂ greenhouse gases over the period from 2000 to 2020. The end result of this report is a set of marginal abatement curves (MACs) that allow for improved understanding of the mitigation potential for non-CO₂ sources, as well as inclusion of non-CO₂ greenhouse gas mitigation in economic modeling. The MAC data sets can be downloaded in spreadsheet format from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

I.2 Non-CO₂ Greenhouse Gases

Greenhouse gases other than CO₂ play an important role in the effort to understand and address global climate change. The non-CO₂ gases include CH₄, N₂O, and a number of high global warming potential or fluorinated gases. The non-CO₂ greenhouse gases are more potent than CO₂ (per unit weight) at trapping heat within the atmosphere and, once emitted, can remain in the atmosphere for either shorter or longer periods of time than CO₂. Figure 2-1 shows that these non-CO₂ greenhouse gases are responsible for approximately 30 percent of the enhanced, anthropogenic greenhouse effect since preindustrial times.

Table 2-1 shows the global total greenhouse gas emissions for the year 2000, broken down by sector and by greenhouse gas type. The non-CO₂ gases constitute 24 percent of the global total greenhouse gas emissions in 2000.

Figure 2-1: Contribution of Anthropogenic Emissions of Greenhouse Gases to the Enhanced Greenhouse Effect from Preindustrial to Present (measured in watts/meter²)

Source: IPCC, 2001b. Note that gases regulated under the Montreal Protocol are excluded.

Table 2-1: Global Greenhouse Gas (GHG) Emissions for 2000 (MtCO₂eq)

Sectors	CO ₂	CH ₄	N ₂ O	High-GWP	Global Total	Percentage of Global Total GHGs
Energy	23,408	1,646	237		25,291	61%
Agriculture	7,631	3,113	2,616		13,360	32%
Industry	829	6	155	380	1,370	3%
Waste		1,255	106		1,361	3%
Global Total	31,868	6,021	3,114	380	41,382	
Percentage of Global Total GHGs	77%	15%	8%	1%		

Source: Adapted from de la Chesnaye et al., in press; USEPA, 2006.

1.2.1 Methane (CH₄)

CH₄ is about 21 times more powerful at warming the atmosphere than CO₂ over a 100-year period.¹ In addition, CH₄'s chemical lifetime in the atmosphere is approximately 12 years, compared with approximately 100 years for CO₂. These two factors make CH₄ a candidate for mitigating global warming in the near term (i.e., within the next 25 years or so) or in the time frame during which atmospheric concentrations of CH₄ could respond to mitigation actions.

¹ Per IPCC (1996) guidelines. The GWP of methane in the IPCC Third Assessment Report (2001a) is 23.

CH₄ is emitted from a variety of manmade sources, including landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes. CH₄ is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent or capture and use CH₄ emissions can provide significant energy, economic, and environmental benefits.

The historical record, based on analysis of air bubbles trapped in glaciers, indicates that CH₄ is more abundant in the Earth's atmosphere now than at any time during the past 400,000 years (National Research Council [NRC], 2001). Since 1750, global average atmospheric concentrations of CH₄ have increased 150 percent, from approximately 700 to 1,745 parts per billion by volume (ppbv) (Intergovernmental Panel for Climate Change [IPCC], 2001a). Although CH₄ concentrations have continued to increase, the overall rate of CH₄ growth during the past decade has slowed. In the late 1970s, the growth rate was approximately 20 ppbv per year. In the 1980s, growth slowed to 9 to 13 ppbv per year. From 1990 to 1998, CH₄ saw variable growth between 0 and 13 ppbv per year (IPCC, 2001a). A recent study by Dlugokencky et al. (2003) shows that atmospheric CH₄ was at a steady state of 1,751 ppbv between 1999 and 2002.

Once emitted, CH₄ is removed from the atmosphere by a variety of processes, frequently called sinks. The balance between CH₄ emissions and CH₄ removal processes ultimately determines atmospheric CH₄ concentrations and determines the length of time CH₄ emissions remain in the atmosphere. The dominant sink is oxidation within the atmosphere by chemical reaction with hydroxyl radicals (OH). Methane reacts with OH to produce alkyl radicals (CH₃) and water in the tropospheric layer of the atmosphere. Stratospheric oxidation also plays a minor role in removing CH₄ from the atmosphere. Similar to tropospheric oxidation, in stratospheric oxidation, minor amounts of CH₄ are destroyed by reacting with OH in the stratosphere. These two reactions account for almost 90 percent of CH₄ removal (IPCC, 2001c). Other known sinks include microbial uptake of CH₄ in soils and the reaction of CH₄ with chlorine (Cl) atoms in the marine boundary layer. It is estimated that these two sinks contribute 7 percent and less than 2 percent of total CH₄ removal, respectively.

1.2.2 Nitrous Oxide (N₂O)

N₂O is a clear, colorless gas with a slightly sweet odor. Because of its long atmospheric lifetime (approximately 120 years) and heat-trapping effects—about 310 times more powerful than CO₂ on a per-molecule basis—N₂O is an important greenhouse gas.

N₂O has both natural and manmade sources and is removed from the atmosphere mainly by photolysis (i.e., breakdown by sunlight) in the stratosphere. In the United States, the main manmade sources of N₂O are agricultural soil management, livestock waste management, mobile and stationary fossil fuel combustion, adipic acid production, and nitric acid production. N₂O is also produced naturally from a variety of biological sources in soil and water. On a global basis, it is estimated that natural sources account for over 60 percent of total N₂O emissions (IPCC, 2001c).

Global atmospheric concentrations of N₂O have increased from about 270 ppbv in 1750 to 314 ppbv in 1998, which equates to a 16 percent increase. In the last 2 decades, atmospheric concentrations of N₂O continue to increase at a rate of 0.25 percent per year. There has been a significant multiyear variance in observed growth of N₂O concentrations, but the reasons for these trends are not fully understood yet (IPCC, 2001b).

I.2.3 High-GWP Gases

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

I.2.3.1 HFCs

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

The HFCs with the largest measured atmospheric abundances are (in order) HFC-23 (CHF_3), HFC-134a ($\text{CF}_3\text{CH}_2\text{F}$), and HFC-152a (CH_3CHF_2). The only significant emissions of HFCs before 1990 were from HFC-23, which is generated as a by-product during the production of HCFC-22. Between 1978 and 1995, HFC-23 concentrations increased from 3 to 10 parts per trillion (ppt), and these concentrations continue to rise. In 1990, HFCs other than HFC-23 were almost undetectable; today, global average concentrations of HFC-134a have risen significantly to almost 10 ppt. HFC-134a has an atmospheric lifetime of about 14 years and its abundance is expected to continue to rise in line with its increasing use as a refrigerant around the world. HFC-152a has increased steadily to about 0.3 ppt in 2000; however, its relatively short lifetime (1.4 years) has kept its atmospheric concentration below 1 ppt (IPCC, 2001a).

I.2.3.2 PFCs

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

PFCs have extremely stable molecular structures and are largely immune to the chemical processes in the lower atmosphere that break down most atmospheric pollutants. Not until the PFCs reach the mesosphere, about 60 kilometers above Earth, are they destroyed by very high-energy ultraviolet rays from the sun. This removal mechanism is extremely slow; as a result, PFCs accumulate in the atmosphere and remain there for several thousand years. The estimated atmospheric lifetimes for CF_4 and C_2F_6 emissions are 50,000 and 10,000 years, respectively. Measurements in 2000 estimated CF_4 global concentrations in the stratosphere at over 70 ppt. Recent relative rates of concentration increase for these two important PFCs are 1.3 percent per year for CF_4 and 3.2 percent per year for C_2F_6 (IPCC, 2001a).

I.2.3.3 Sulfur Hexafluoride (SF_6)

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

semiconductors and flat panel displays; and (4) for a variety of smaller uses, including uses as a tracer gas and as a filler for sound-insulated windows.

Like the PFCs, SF₆ is very long lived, so all manmade sources contribute directly to its accumulation in the atmosphere. Measurements of SF₆ show that its global average concentration increased by about 7 percent per year during the 1980s and 1990s, from less than 1 ppt in 1980 to almost 4 ppt in the late 1990s (IPCC, 2001a).

I.2.4 Use of GWPs in this Report

The GWP compares the relative ability of each greenhouse gas to trap heat in the atmosphere during a certain time frame. Per IPCC (1996) guidelines, CO₂ is the reference gas and thus has a GWP of 1. Based on a time frame of 100 years, the GWP of CH₄ is 21 and the GWP of N₂O is 310. Table 2-2 lists all GWPs used in this report to convert the non-CO₂ emissions into CO₂-equivalent units. This report uses GWPs from the 1996 IPCC Second Assessment Report (rather than the 2001 Third Assessment Report) because these are the values specified by greenhouse gas reporting guidelines under the United Nations Framework Convention on Climate Change.

Table 2-2: Global Warming Potentials

Gas	GWP
Carbon dioxide (CO ₂)	1
Methane (CH ₄)	21
Nitrous oxide (N ₂ O)	310
HFC-23	11,700
HFC-125	2,800
HFC-134a	1,300
HFC-143a	3,800
HFC-152a	140
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF ₄	6,500
C ₂ F ₆	9,200
C ₄ F ₁₀	7,000
C ₆ F ₁₄	7,400
SF ₆	23,900

I.3 Methodology

This section describes the basic methodology used in this report to analyze potential emissions and abatement of non-CO₂ greenhouse gases. In this analysis we construct MAC curves for each region and sector by estimating the carbon price at which the present value benefits and costs for each mitigation option equilibrates. The methodology produces a stepwise curve, where each point reflects the average price and reduction potential if a mitigation technology were applied across the sector within a given region. This section describes the components of our methodology. First, we establish the baseline emissions for each sector in Section I.3.1. Then we describe the methodology used to evaluate mitigation options in Section I.3.2, which involves calculating the abatement potential and the

breakeven price for each option. Lastly, we describe the construction of the MACs in Section I.3.3. Some sectors deviate from this methodology depending on specific circumstances, which are briefly mentioned here and described in more detail in the sector-specific chapters.

The results of the analysis are presented as MACs by region and by sector and generally focus on or within the 2000 to 2020 time frame. In some cases, sensitivities to the MACs are presented where the discount rate, tax rate, and energy prices vary. Emissions abatement in the MACs is shown as both absolute emissions reductions and as percentage reductions from the baseline. Non-CO₂ emissions sources analyzed in this report are coal mining; natural gas production, processing, transmission, and distribution; oil production; solid waste management; wastewater; specialized industrial processes; and agriculture.

I.3.1 Baseline Emissions for Non-CO₂ Greenhouse Gases

Current and projected (through 2020) emissions estimates are based primarily on emissions projections from the USEPA's *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The methods used to estimate and project non-CO₂ emissions in USEPA (2006) are briefly summarized here. In some cases, particularly for the fluorinated gas emissions and agricultural emissions, it was necessary to develop separate baselines from which to assess the mitigation analyses. These deviations are also explained in this report.

For Annex I countries,² baseline (i.e., reference) projections are based largely on publicly available reports produced by the countries themselves. The preferred sources for these reports are the *National Communications* for the United Nations Framework Convention on Climate Change,³ which contain current emissions rates and emissions projections through 2020. Estimates from the various countries should be comparable because they rely on the same (or similar) IPCC methodologies and country-specific activity data.

Estimates of historical and projected emissions for developing countries were based on national and international reports. These emissions rates also reflect the most recent results of the USEPA study *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The preferred approach to estimate emissions from developing countries is to use the latest published information for each country. Some developing countries reported emissions estimates from 1990 or later in the latest *National Communications*, in *Asia Least-Cost Greenhouse Gas Abatement Strategy* (ALGAS) (Asian Development Bank, 1998), or in a country-specific report. Preference is given to the latest published estimates from the *National Communications* and ALGAS reports, including both historical and projected estimates.

When the emissions data from these references did not cover the entire historical or projected period from 1990 to 2020, or in cases where no emissions data were reported, estimated emissions were obtained using the following approaches:

1. For countries reporting estimates from 1990 to 2010 in 10-year intervals, a linear interpolation was used to estimate values in 5-year increments.

² Annex I countries are countries that are listed in Annex I to the United Nations Framework Convention on Climate Change. A complete list of the Annex I countries is available at http://unfccc.int/essential_background/convention/background/items/1346.php.

³ The *National Communications* are available at <http://www.unfccc.org>.

2. For countries not reporting emissions through 2000, emissions growth rates were estimated based on IPCC Tier 1⁴ estimates for the country for 1990 through 2000. The growth rates were applied to reported inventories since 1990 and used to estimate the remaining years through 2000. Projections to 2020 are based on growth-rate projections applied to source-specific drivers for each country, using the estimate for 2000 as the base year.
3. When no emissions data were available or when the data were insufficient, the USEPA developed emissions estimates, projections, or both, using the default methodology presented in the *1996 Revised IPCC Guidelines* (IPCC, 1997) and the *IPCC Good Practice Guidance* (IPCC, 2000).

Baseline projections represent business-as-usual scenarios, where currently achieved reductions are incorporated, but future mitigation actions are only included if either a well-established program or an international sector agreement is in place. Thus, projections do not include planned climate change source-level mitigation efforts, although they do include voluntary and nonclimate-based policies that indirectly reduce greenhouse gases. For consistency, if a country's reported projections include planned climate mitigation efforts, the reductions from those efforts were added back into the emissions projections, where identified. If planned climate policy reductions could not be identified, a country's emissions projections were estimated by continuing trends from previous years, as reported in historical inventories.

Source-by-source and country-by-country explanations of how the projections were developed can be found in the appendix to USEPA (2006).

I.3.1.1 Baseline Emissions for Agriculture

For the agricultural mitigation analysis, separate baseline emissions for croplands and rice cultivation were developed and used, even though USEPA (2006) includes estimates for these sources. Process-based models—DAYCENT for croplands and DeNitrification-DeComposition (DNDC) for rice cultivation—were used for both the baseline emissions estimates and the greenhouse gas implications of mitigation options, thus allowing for a clear identification of baseline management conditions and consistent estimates of changes to those conditions through mitigation activities. For emissions associated with livestock, the mitigation analysis in this report relies on USEPA (2006) baseline estimates. Further details about the emissions baselines estimated by the DAYCENT and DNDC models, and their relationship to USEPA (2006) estimates, are provided in Section V Agriculture of this report.

I.3.1.2 Baseline Emissions for Fluorinated Gases

Baselines for the fluorinated gases are also based on *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006). The 2006 USEPA analysis builds on the 2001 USEPA analysis to develop country-by-country and industry-by-industry projections of emissions using projections of activity data, emissions factors, or other data related to emissions. For the industrial sources, activity data were multiplied by emissions factors to obtain emissions projections. For the substitutes for ODSs, estimates of country-specific ODS consumption as reported under the Montreal Protocol were used in conjunction with output from the USEPA's Vintaging Model to project emissions. Activity data and activity growth projections were obtained from a variety of sources, including international industry trade organizations and databases, U.S. government agencies, and international organizations. For all industries, country-specific estimates of activity (or a factor related to activity) were available. Information on emissions rates was generally less precise but was often available on a regional, if not country-specific, basis.

⁴ Tier 1 refers to the emissions factor estimation methodology in the IPCC guidelines with the highest level of implied accuracy in emissions estimation in a hierarchy of methodology tiers.

For industrial sources of fluorinated gases, this report presents international baselines and MACs for five industrial sources of HFCs, PFCs, and SF₆, including the production of aluminum, magnesium, semiconductors, and HCFC-22, and the use of electrical equipment in electric power systems. For all five of these sources, two sets of baselines and MACs are presented: the technology-adoption baseline, based on the assumption that the industries will achieve their announced global emissions reduction goals for the year, and the no-action baseline, based on the assumption that the industries' emissions rates will remain constant. Detailed discussions of the methodology used to develop the baselines for each source can be found in USEPA (2006).

In addition to the industrial sectors, this report also includes estimates of fluorinated gases that are used as substitutes for ODSs. The USEPA's Vintaging Model and industry data were used to simulate the aggregate impacts of the ODS phaseout on the use and emissions of various fluorocarbons and their substitutes in the United States. Emissions estimates for non-U.S. countries incorporate estimates of the consumption of ODSs by country, as provided by the United Nations Environment Programme (UNEP) (1999). The estimates for the European Union (EU) were provided in aggregate, and each country's gross domestic product (GDP) was used as a proxy to divide the consumption of the individual member nation by the EU total. Estimates of country-specific ODS consumption, as reported under the Montreal Protocol, were then used in conjunction with Vintaging Model output for each ODS-consuming sector. In the absence of country-level data, preliminary estimates of emissions were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in economic growth, rates of ODS phaseout, and the distribution of ODS use across end-uses in each region or country, as explained in Section IV Industrial Processes in this report.

I.3.2 Mitigation Option Analysis Methodology

Although non-CO₂ emissions from each sector are estimated according to the available data and issues important to that sector, the mitigation option analysis throughout this report was conducted using a common methodology. This section outlines the basic methodology. The sector-specific chapters describe the mitigation estimation methods in greater detail, including any necessary deviations from the basic methodology. Mitigation options represented in the MACs of this report are applied to the baselines described in Section I.3.1.

The abatement analysis for all non-CO₂ gases for agriculture, coal mines, natural gas systems, oil systems, landfills, wastewater treatment, and nitric and adipic acid production are based on and improve upon DeAngelo et al. (in press), Delhotal et al. (in press), and Ottinger et al. (in press); two previous USEPA studies for the United States (USEPA, 2001, 1999); and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH₄ abatement for EU members from 1990 to 2010. These studies provided estimates of potential CH₄ and N₂O emissions reductions from major emitting sectors and quantified costs and benefits of these reductions.

The EC study evaluates the abatement potential and cost options at representative facilities or point sources of emissions, such as waste digesters, and then extrapolates the results to a country and to the EU level. Given the more detailed data available for U.S. estimates, the USEPA's U.S. analysis also uses representative facility estimates but then applies the estimates to a highly disaggregated and detailed set of emissions sources for all the major sectors and subsectors. For example, the USEPA analysis of the natural gas sector is based on more than 100 emissions sources in that industry, including gas well

equipment, pipeline compressors and equipment, and system upsets. Thus, the EC analysis provides more of a sector-average cost for individual abatement options at the country or EU level, while the USEPA analysis provides more detail at the sector and subsector levels.

For this report, average U.S. abatement costs and benefits are estimated for each abatement option to build a set of regional options and estimates comparable to that for the EU. Together, this new combined set of abatement options is applied to all defined regions in the study, both the United States and the EU, as well as to regions where data and detailed analyses are unavailable. The advantage of using the “average” approach over the more detailed analyses for the United States and the EU is that the approach incorporates the latest emissions estimated and compiled in USEPA (2006) and provides for a consistent methodology throughout the analysis for all regions. It should be noted that mitigation estimates from this “average” approach are more conservative than those reported in the USEPA and EC reports.

For the high-GWP abatement analysis, it is assumed that some mitigation technologies are adopted to meet industry reduction targets. Therefore, some mitigation options are accounted for in the baseline emissions. If an option is assumed to be adopted in the baseline, it is not included when generating the MAC. In addition, expert judgment determines market penetration rates of mitigation technologies competing for the same set of fluorinated gas emissions.

The agricultural sector’s emissions abatement analysis improves upon a previous study supported by the USEPA (DeAngelo et al., in press) that generated MACs by major world region for cropland N_2O , livestock enteric CH_4 , manure CH_4 , and rice CH_4 for the year 2010. The most significant change in this report is the use of biophysical, process-based models (i.e., DAYCENT and DNDC) to better capture the net greenhouse gas and yield effects and to capture the spatial and temporal variability of those effects for the cropland and rice emissions baseline and mitigation scenarios. Use of these process-based models is intended to show broad spatial and temporal baseline trends and broad changes when mitigation scenarios are introduced, rather than to show definitive absolute emissions numbers for specific locations. Additional mitigation options are now assessed (e.g., slow-release fertilizers, nitrogen (N)-inhibitors, and no-till), and more detailed, less aggregated results are provided for individual crop types under both irrigated and rainfed conditions. Improved agriculture MACs are generated for 2000, 2010, and 2020.

1.3.2.1 Technical Characteristics of Abatement Options

The non- CO_2 abatement options evaluated in this report are compiled from the studies mentioned above, as well as from the literature relevant for each sector. For each region, either the entire set of sector-specific options or the subset of options determined to be applicable is applied. Options are omitted from individual regions on a case-by-case basis, using either expert knowledge of the region or technical and physical factors (e.g., appropriate climate conditions). In addition, the rate or extent of penetration of an option into the market within different regions may vary based on these conditions. The selective omission of options represents a static view of the region’s socioeconomic conditions. Ideally, more detailed information on country-specific conditions, technologies, and experiences will be available in the future, which will enable more rigorous analyses of abatement option availability over time in each region. The average technical lifetime of an option (in years) is also determined using expert knowledge of the technology or recent literature, as referenced in each section of this report.

Table 3-1 summarizes how the abatement potential is calculated for each of the available abatement options. The total abatement potential of an option for each region is equal to an option’s technical applicability multiplied by its implied adoption rate multiplied by its reduction efficiency. Total baseline emissions are summed from each of the emissions sources within each sector and each region. Each

Table 3-1: Abatement Potential Calculation for Mitigation Options

Technical applicability (%)	X	Implied adoption rate (%)	X	Reduction efficiency (%)	=	Abatement potential (%)
Percentage of total baseline emissions from a particular emissions source to which a given option can be potentially applied.		Percentage of technically applicable baseline emissions to which a given option is applied; avoids double counting among overlapping options and fixes penetration rate of options relative to each other. ^a		Percentage of technically achievable emissions abatement for an option after it is applied to a given emissions stream.		Percentage of baseline emissions that can be reduced at the national or regional level by a given option. Product of technical applicability, implied adoption rate, and reduction efficiency of the option.

^a Implied adoption rate for nonoverlapping options (i.e., applicable to different emissions streams) is assumed to add to 100 percent of technically applicable baseline emissions.

mitigation option reduces baseline emissions by the reduction efficiency percentage of the relevant portion of the total baseline emissions, as defined by the technical applicability and implied adoption rate.

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

The implied adoption rate of an option is a mathematical adjustment for other qualitative factors that may influence the effectiveness of a mitigation option. For the energy, waste, and agriculture sectors, it was outside the scope of this analysis to account for adoption feasibility, such as social acceptance and alternative permutations in the sequencing of adoption. The implied adoption rate of each of the n overlapping options is equal to $1/n$, which avoids cumulative reductions of greater than 100 percent across options. Given the lack of region-specific data for determining the relative level of diffusion among options that could compete for the same emissions stream, we applied this conservative adjustment. When nonoverlapping options are applied, they affect 100 percent of baseline emissions from the relevant source. Examples of two nonoverlapping options in the natural gas system are inspection and maintenance of compressors and replacement of distribution pipes. These options are applied independently to different parts of the sector and do not compete for the same emissions stream. An example of overlapping options is the sequencing of cropland mitigation options, where the adoption of one option (e.g., conversion to no tillage) affects the effectiveness of subsequent options (e.g., reduced fertilizer applications). While this describes the basic application of the implied adoption rate in the energy, waste, and agriculture sectors, this factor is informed by expert insight into the potential market penetration over time in the industrial processes sector.

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

Once the total abatement potential of an option is calculated as described above, the abatement potential is multiplied by the baseline emissions for each sector and region to calculate the absolute

amount of emissions reduced by employing the option. The absolute amount of baseline emissions reduced by an option in a given year is expressed in million metric tons of CO₂ equivalent (MtCO₂eq).⁵

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

1.3.2.2 Economic Characteristics of Abatement Options

Each abatement option is characterized in terms of its costs and benefits per an abated unit of gas (tCO₂eq or tons of emitted gas [e.g., tCH₄]).

For each mitigation option, the carbon price (P) at which that option becomes economically viable can be calculated (i.e., where the present value of the benefits of the option equals the present value of the costs of implementing the option). A present value analysis of each option is used to determine breakeven abatement costs in a given region. Breakeven calculations are independent of the year the mitigation option is implemented but are contingent on the life expectancy of the option. However, in the energy and waste sectors, sensitivities are conducted to examine the implication of time. The net present value calculation solves for breakeven price P , by equating the present value of the benefits with the present value of the costs of the mitigation option. More specifically,

$$\underbrace{\sum_{t=1}^T \left[\frac{(1-TR)(P \cdot ER + R) + TB}{(1+DR)^t} \right]}_{\text{Net Present Value Benefits}} = \underbrace{CC + \sum_{t=1}^T \left[\frac{(1-TR)RC}{(1+DR)^t} \right]}_{\text{Net Present Value Costs}} \quad (3.1)$$

where

- P = the breakeven price of the option (\$/tCO₂eq);
- ER = the emissions reduction achieved by the technology (MtCO₂eq);
- R = the revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost) or change in agricultural commodity prices (\$);
- T = the option lifetime (years);
- DR = the selected discount rate (%);
- CC = the one-time capital cost of the option (\$);
- RC = the recurring (O&M) cost of the option (portions of which may be scaled based on regional labor costs) (\$/year);
- TR = the tax rate (%); and
- TB = the tax break equal to the capital cost divided by the option lifetime, multiplied by the tax rate (\$).

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

⁵ One MtCO₂eq equals 1 teragram of CO₂ equivalent (TgCO₂eq): 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

$$P = \frac{CC}{(1-TR)ER \sum_{t=1}^T \frac{1}{(1+DR)^t}} + \frac{RC}{ER} - \frac{R}{ER} - \frac{CC}{ER \cdot T} \cdot \frac{TR}{(1-TR)} \quad (3.2)$$

Costs include capital or one-time costs and operation and maintenance (O&M) or recurring costs. Additionally, some one-time costs (where data are available) are subdivided into labor and equipment components. Recurring costs may also be subdivided into labor costs, fertilizer costs, and other cost components. Benefits or revenues from employing an abatement option can include (1) the intrinsic value of the recovered gas (e.g., the value of CH₄ either as natural gas or as electricity/heat, the value of HFC-134a as a refrigerant), (2) nongreenhouse gas benefits of abatement options (e.g., compost or digestate for waste diversion options, increases in crop yields), and (3) the value of abating the gas given a greenhouse gas price in terms of dollars per tCO₂eq (\$/tCO₂eq) or dollars per metric ton of gas (e.g., \$/tCH₄, \$/tHFC-134a). In most cases, there are two price signals for the abatement of CH₄: one price based on CH₄'s value as energy (because natural gas is 95 percent CH₄) and one price based on CH₄'s value as a greenhouse gas. All cost and benefit values are expressed in constant year 2000 U.S. dollars.

Costs and benefits of abatement options are adjusted based on energy and labor costs in corresponding regions. If not otherwise available, the equipment component of fixed costs is not adjusted and stays the same for all regions. Most of the agricultural sector options, such as changes in management practice, do not have applicable capital costs, with the exception of anaerobic digesters for manure management. In general, labor costs comprise the majority of O&M costs. Given this fact, we have used labor costs as a proxy to adjust O&M costs across regions, as well as the labor component of the one-time cost. Specifically, O&M costs for each region are estimated based on a ratio between the average regional labor cost in manufacturing in that region and in the United States for U.S.-based options or the EU for EU-based options. Regional labor costs in manufacturing are taken from World Bank data (2000). For the agricultural sector, labor costs are calculated labor shares of agricultural production costs from the Global Trade Analysis Project (GTAP) and agricultural wage data from the International Food Policy Research Institute (IFPRI).

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

In regions where there is a lack of detailed revenue data, revenues are scaled based on the ratio between average prices of natural gas (when CH₄ is abated and sold as natural gas) or of electricity (when CH₄ is used to generate electricity or heat) in a given region and in the United States or EU. Similarly, revenues from non-CH₄ benefits of abatement options are scaled based on the ratio between the GDPs per capita in a given region and in the United States or EU. In the agricultural sector, changes in revenue occur as a change in either crop yield or livestock productivity. Data on changes in crop yield or livestock productivity are combined with data on regional producer prices for the relevant agricultural commodity to calculate revenue changes.

This analysis is conducted using a 10 percent discount rate and a 40 percent tax rate. In some sectors, sensitivities on alternative discount and tax rates illustrate different social and industry perspectives. Sensitivities with a social perspective use lower discount rates and a zero percent tax rate, while sensitivities with an industry perspective assume higher discount rates and greater than zero tax rates. For quick reference, Table 3-2 lists the basic financial assumptions used throughout this report. In addition, because of the high sensitivity to energy prices, the analysis tests the MAC sensitivity to

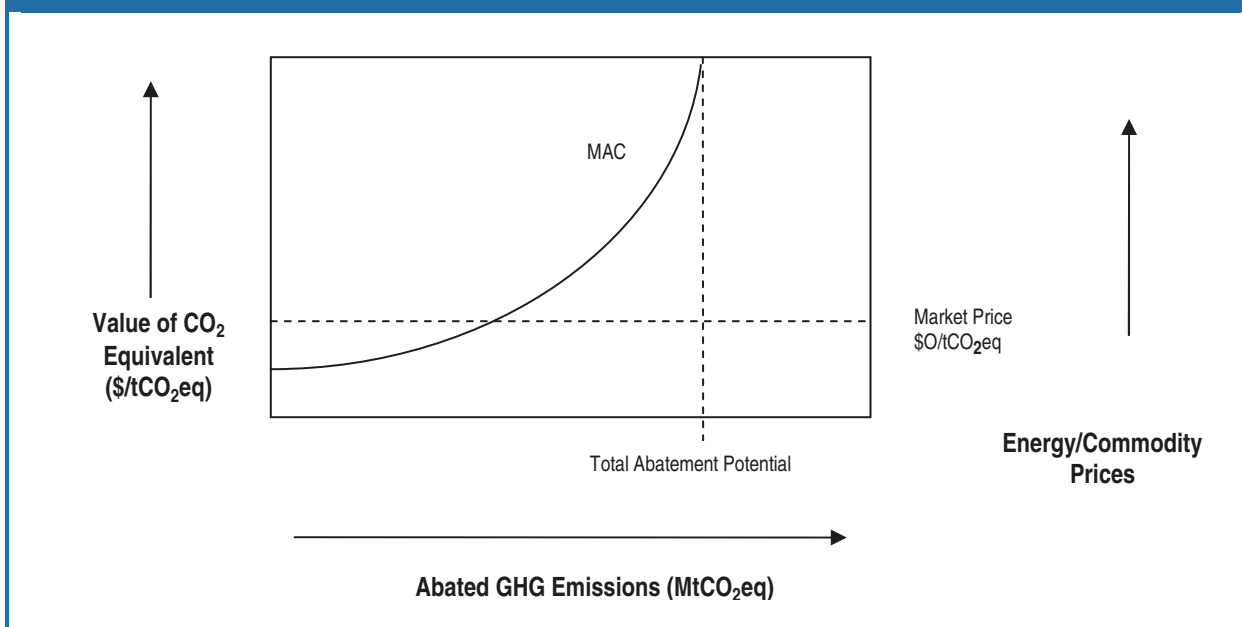
Table 3-2: Financial Assumptions in Breakeven Price Calculations for Abatement Options

Variable	Assumption
Discount rate	10%
Tax rate	40%
Year dollars	2000\$

changes in base energy price (from –50 percent to 200 percent) for both electricity and natural gas, where this sensitivity test is relevant to the sector. The energy price assumptions are also included in the TechTables.xls file in the appendices to the *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21* on the USEPA’s Web site <<http://www.epa.gov/nonco2/econ-inv/international.html>> (USEPA, 2005).

I.3.3 Marginal Abatement Curves

MACs are used to show the amount of emissions reduction potential at varying price levels. In theory, a MAC illustrates the cost of abating each additional ton of emissions. Figure 3-1 shows an illustrative MAC. The x-axis shows the amount of emissions abatement in MtCO₂eq, and the y-axis shows the breakeven price in \$/tCO₂eq required to achieve the level of abatement. Therefore, moving along the curve, the lowest cost abatement options are adopted first. The curve becomes vertical at the point of maximum total abatement potential, which is the sum of abatement across all options in a sector or region.

Figure 3-1: Illustrative Non-CO₂ Marginal Abatement Curve

In Figure 3-1, the commodity/energy market price is aligned to \$0/tCO₂eq since this price represents the point at which no additional price signals exist from GHG credits to motivate emissions reductions; all emissions reductions are due to increased energy efficiencies, conservation of production materials, or both. As a value is placed on GHG reductions in terms of \$/tCO₂eq, these values are added to the

commodity/energy market prices and allow for additional emissions reductions to clear the market. The points on the MAC that appear at or below the zero cost line (\$0/tCO₂eq) illustrate this dual price-signal market. These “below-the-line” amounts represent mitigation options that are already cost-effective given the costs and benefits considered (and are sometimes referred to as “no-regret” options) yet have not been implemented because of the existence of nonmonetary barriers.

The MACs in this report are constructed from bottom-up average breakeven price calculations. The average breakeven price is calculated for the estimated abatement potential for each mitigation option (see Section I.3.2.2). The options are then ordered in ascending order of breakeven price (cost) and plotted against abatement potential. The resulting MAC is a stepwise function, rather than a smooth curve, as seen in the illustrative MAC (Figure 3-1), because each point on the curve represents the breakeven price point for a discrete mitigation option (or defined bundle of mitigation strategies). Conceptually, marginal costs are the incremental costs of an additional unit of abatement. However, the abatement cost curves developed here reflect the incremental costs of adopting the next cost-effective mitigation option. We estimated the costs and benefits associated with all or nothing adoption of each well-defined mitigation practice. We did not estimate the marginal costs of incremental changes within each practice (e.g., the net cost associated with an incremental change in paddy rice irrigation). Instead, the MACs developed in this report reflect the average net cost of each option for the achieved reduction (*ER* in Equations 3.1 and 3.2). When data were not available to clearly identify marginal abatement roles for mitigation technologies because of either (a) the potential for abatement of the same share of baseline emissions, or (b) sensitivities to the order of adoption, we employed the implied adoption rate (Table 3-1).

In the energy and waste sectors, representative facilities facing varied mitigation costs employ mitigation technologies based on the lowest average breakeven option price. In calculating the abatement potential, options are evaluated according to whether they are complements or substitutes. If a group of options are complements (or independent of one another), the implied adoption rates are all equal to one. If options are substitutes for each other, the lowest price option is selected for each representative facility; in this way, the implied adoption rate for each technology is estimated.

In the industrial processes sector, mitigation options are applied to one representative facility, in order of lowest average breakeven price to highest average breakeven price. Each option is applied to a portion of the baseline emissions based on the implied adoption rate (the $1/n$ factor, as described in Section I.3.2.1), which, in the industrial sector, is informed by expert insight into potential adoption rates of various mitigation technologies.

In the agriculture sector, mitigation options are applied to representative farms of each region based on the lowest average breakeven price. The implied adoption rate is based purely on the number of available migration options ($1/n$), where each option is applied to an equal portion of the cropland base or livestock population and, thus regional baseline emissions, for each region over time. Given the existence of nonprice and implementation factors that influence market share and the lack of accurate and detailed information regarding these qualitative characteristics, we assume an even distribution of options across the baseline for the agriculture sector. This approach allows options to share a portion of market penetration, regardless of their cost-effectiveness, rather than allowing only the least-cost option to completely dominate the market. Our methodology is more conservative than if we had assumed only price factors exist, thus allowing the least-cost option to penetrate the sector by 100 percent.

The MACs represent the average economic potential of mitigation technologies in that sector, because it is assumed that if a mitigation technology is technically feasible in a given region, then it is implemented according to the relevant economic conditions. Therefore, the MACs do not represent the market potential or the social acceptance of a technology. The models used in the analysis are static (i.e.,

they do not represent adoption of mitigation technologies over time). This analysis assumes partial equilibrium conditions that do not represent economic feedbacks from the input or output markets. This analysis makes no assumptions regarding a policy environment that might encourage the implementation of mitigation options. Additional discussion of some key limitations of the methodology is provided in Section I.5.

The end result of this analysis is a tabular data set for the MACs by sector, gas, and region, which are presented in Appendix A.⁶ Sectoral MACs are aggregated by gas and by region to create global MACs, which are presented in Section I.4.

I.3.4 Methodological Enhancements from Energy Modeling Forum Study

This report builds on a study previously conducted by the USEPA for Stanford's EMF-21. The EMF-21 focused specifically on multigas strategies and the incorporation of non-CO₂ greenhouse gas data sets into economic models. Although this analysis is built largely on the previous USEPA analysis for the EMF-21, we have made several key enhancements.

In the energy and waste sectors, new sensitivity cases illustrate the effect of technical change over time. Introducing technical change by incorporating the rate of change of technical applicability can potentially shift the MAC down and to the right on the graph, as abatement potential increases and net costs decrease at a given carbon price.

For industrial sources of fluorinated gases, the emissions baselines have been updated since the EMF-21 analysis. The analysis included one set of baseline emissions for industrial sources, while this report presents two sets of baselines for aluminum, magnesium, and semiconductor manufacturing. One baseline set assumes industry agreements establishing emissions reduction targets will be upheld, while the other baseline set assumes that the industry agreement has no effect on the baseline emissions. In addition, the MACs for aluminum manufacturing and electrical power systems have been enhanced with additional data.

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

In the agricultural sector, the previous methodology is improved on for this analysis by using the biophysical, process-based models DAYCENT and DNDC. These models capture the net greenhouse gas effects of the cropland and rice baseline emissions and mitigation options, and they reflect the heterogeneous emissions and yield effects of adopting mitigation practices. In addition, new agricultural mitigation options are now assessed, and more detailed results are provided for individual crop types. Finally, the agricultural commodity market effects are explored with a global agricultural trade model (IMPACT of the IFPRI).

⁶ Tables are presented that provide the percentage abatement for a series of breakeven prices. The MAC data are presented as tables so that exact values can be determined for use in modeling activities.

I.4 Aggregate Results

Worldwide, 2005 total non-CO₂ anthropogenic greenhouse gas baseline emissions are estimated to be 10,278 MtCO₂eq and are projected to increase by 27 percent to 13,013 MtCO₂eq by 2020. These gases are emitted from four major emitting sectors: the energy, waste management, industrial processes, and agricultural industries. China, India, the United States, Brazil, and the European Union are the world's five largest emitters and account for approximately 76 percent of total non-CO₂ emissions.

This section presents the forecasted baseline emissions and provides a global overview of the results from the MAC analysis by sector and for the five largest emitting regions. The data represented in this chapter are aggregated and provide a summary of all sources and non-CO₂ greenhouse gases. The individual chapters are organized by source and present the full details of these analyses. For a complete data set of mitigation potential by sector, gas, and region, refer to Appendix A.

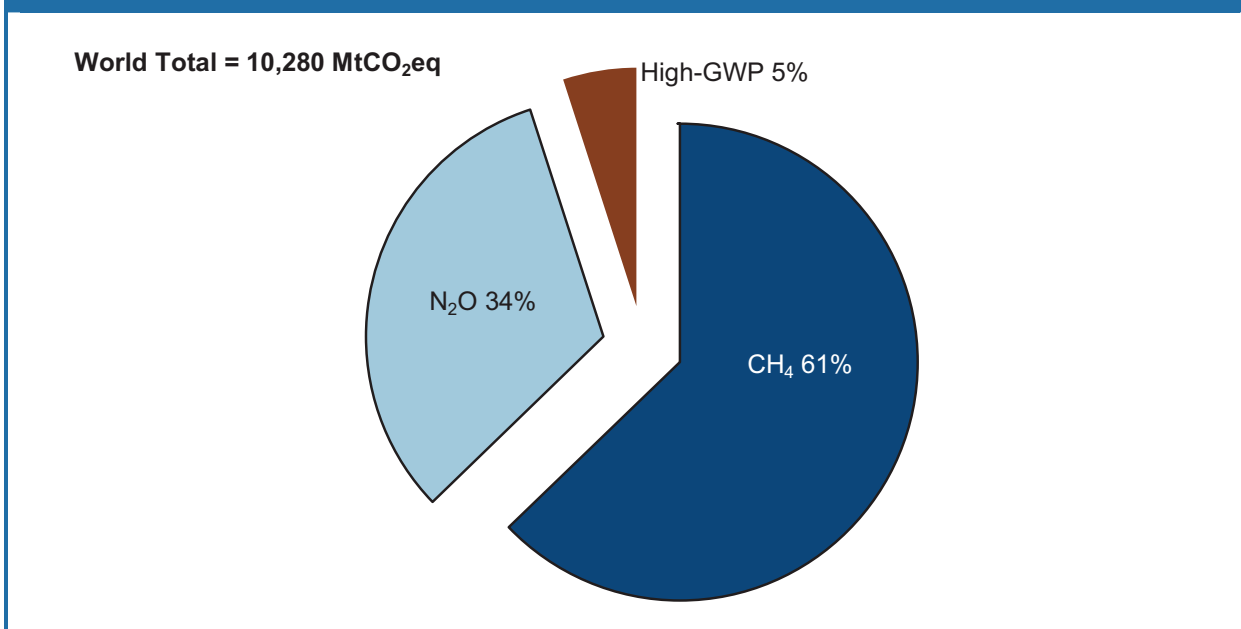
For the purposes of aggregation, the results from the “technology adoption” baseline were used from industrial process subsectors with dual baselines. In the agriculture sector, the MAC data from the “constant area” scenarios were used, while the baselines from *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006) were used for consistency across the sectors in aggregation.

I.4.1 Baselines

I.4.1.1 By Non-CO₂ Greenhouse Gas

Figure 4-1 provides information on the relative share of each greenhouse gas that comprises the global non-CO₂ greenhouse gas baseline emissions total. CH₄ represents the largest share of emissions worldwide, accounting for approximately 61 percent of the total non-CO₂ emissions in 2005, while N₂O and high-GWP gases accounted for 34 percent and 5 percent, respectively.

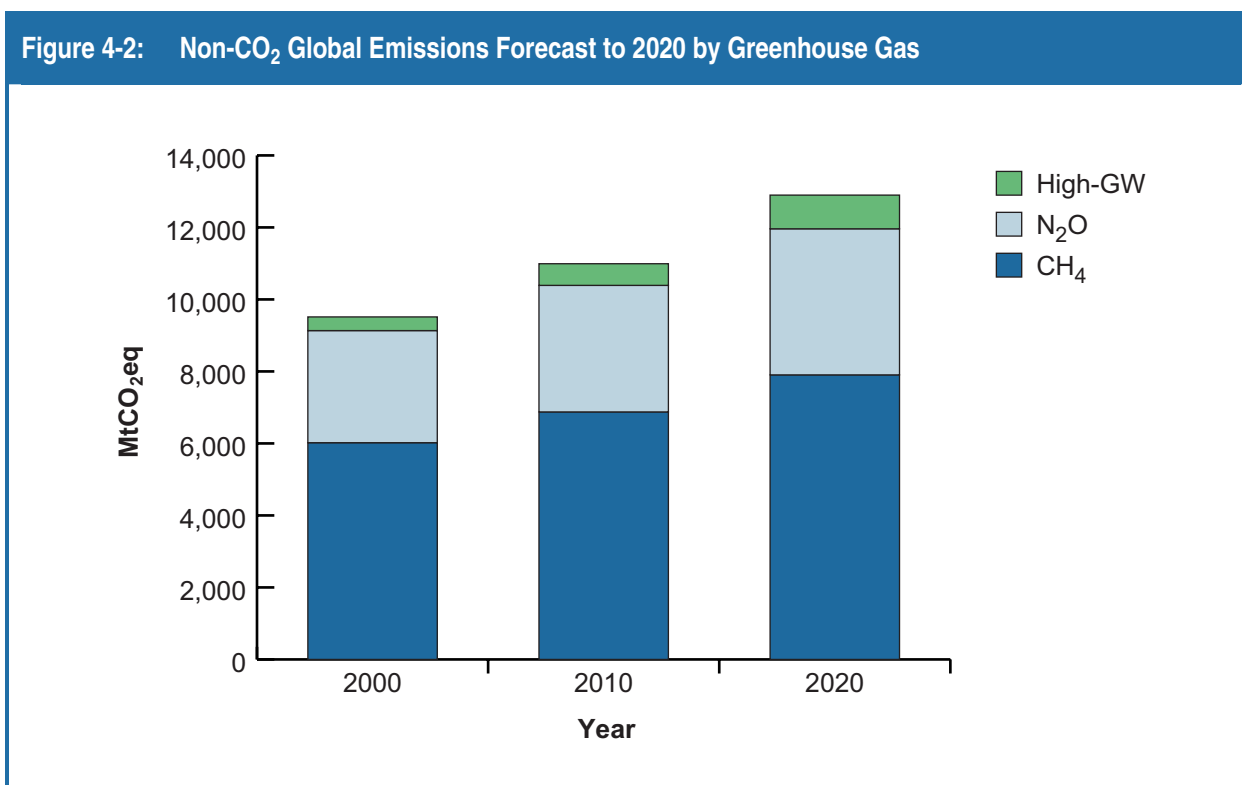
Figure 4-1: Percentage Share of Global Non-CO₂ Emissions^a by Type of Gas in 2005



Source: USEPA, 2006.

^a CO₂ equivalency based on 100-year GWP.

Figure 4-2 presents the projected baseline emissions by greenhouse gas for 2000, 2010, and 2020. The distribution of non-CO₂ greenhouse gases is forecasted to remain relatively unchanged through 2020. The most significant change is represented by a projected increase in the relative share of high-GWP gases with respect to CH₄ and N₂O, growing from 5 percent to more than 7 percent of global non-CO₂ emissions between 2005 and 2020.

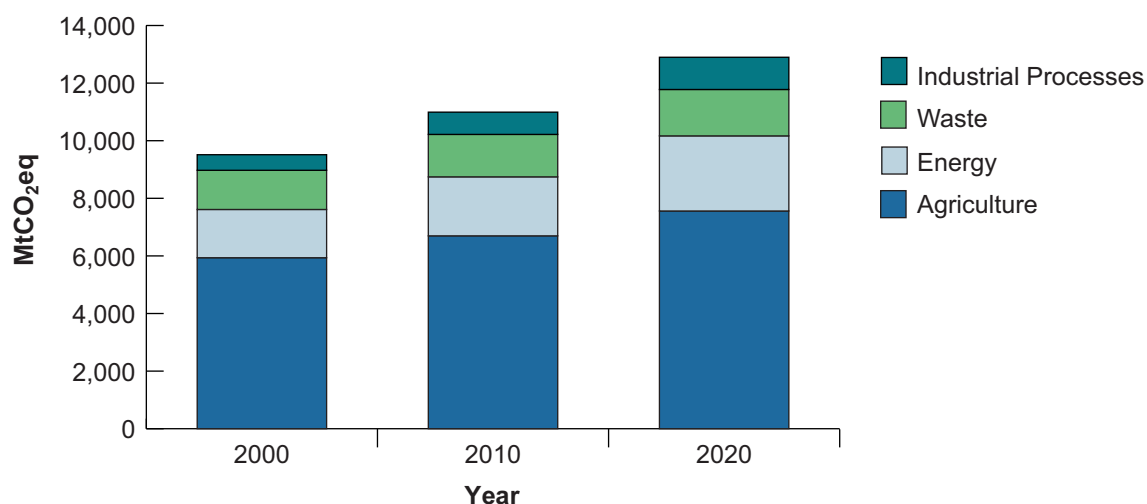


Source: USEPA, 2006.

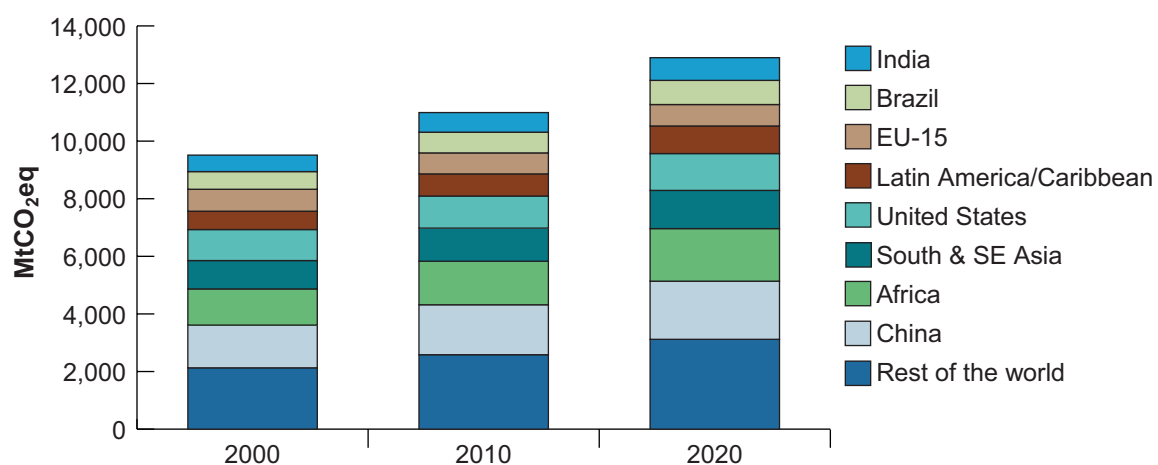
I.4.1.2 By Major Emitting Sectors and Countries

The sources of non-CO₂ emissions are categorized into four major emissions sectors: energy, waste, industrial processes, and agriculture. Figures 4-3 and 4-4 provide the projected global emissions baseline for 2000, 2010, and 2020, by major emissions sector and by major emitting region, respectively. The agriculture sector includes soil and manure management, rice cultivation, enteric fermentation, and other nonindustrial sources such as biomass burning. Emissions sources categorized in the energy sector include coal mining activities, natural gas transmission and distribution, and gas and oil production. The waste sector includes municipal solid waste management, as well as human sewage and other types of wastewater treatment. The industrial processes sector includes a wide range of activities, such as semiconductor manufacturing, primary aluminum production, and electricity transmission and distribution.

Agriculture is the primary source of non-CO₂ emissions, accounting for 60 percent of the total 2010 baseline. Energy is the second largest emissions producer, representing 20 percent of the total baseline. The waste sector represents 14 percent of the total baseline, and the industrial processes sector represents 7 percent.

Figure 4-3: Global Emissions by Major Sector for All Non-CO₂ Greenhouse Gases

Source: USEPA, 2006. Note that this mitigation analysis uses baseline emissions projections for croplands and rice (within agriculture) that differ from USEPA (2006)

Figure 4-4: Projected World Emissions Baselines for Non-CO₂ Greenhouse Gases, Including the Top Emitting Regions

Source: USEPA, 2006.
EU-15 = European Union.

Figure 4-4 shows the projected emissions baselines for the world, as well as the largest emitting countries. The largest non-CO₂ emitting countries are typically characterized as mature, highly industrialized countries or countries with significant agricultural sectors. In 2005, the top five emitting countries—China, the United States, EU-15, Brazil, and India—account for 44 percent of the world’s total non-CO₂ emissions, and their relative contribution to the world baseline is projected to remain the same during the next 15 years.

I.4.2 Global MACs

The MAC analysis methodology outlined in Section I.3 of this report develops bottom-up projections of potential reductions in non-CO₂ emissions in terms of the breakeven price (\$/tCO₂eq). The emissions reduction potential is constrained by technology limitations, as well as by regional and geographical applicability. In this report, MACs are developed for each major source by sector and country. The resulting series of MACs are aggregated up across sectors, gases, and regions. The MACs indicate the potential reduction in non-CO₂ gas emissions for a given breakeven price. Figure 4-5 presents the results from the MAC analysis for 2020 by major economic sector. Figure 4-6 presents aggregate MACs by greenhouse gas type for 2020. Figure 4-7 presents the 2020 MACs for the world’s largest non-CO₂ greenhouse gas emitting regions.

Figure 4-5: Global 2020 MACs for Non-CO₂ Greenhouse Gases by Major Sector

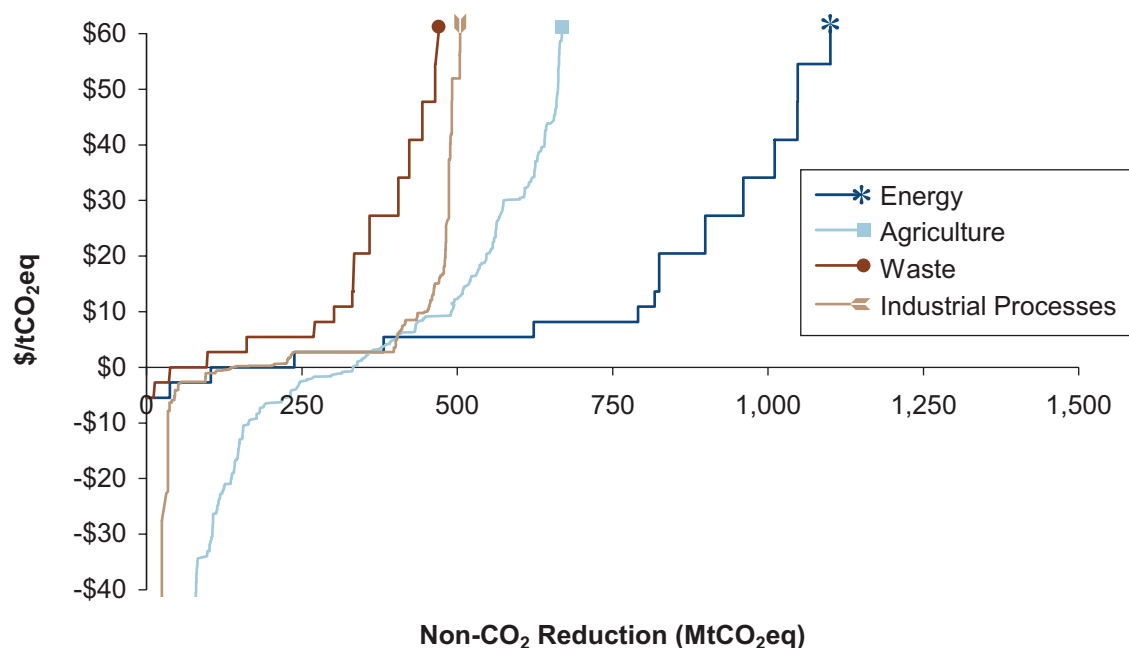
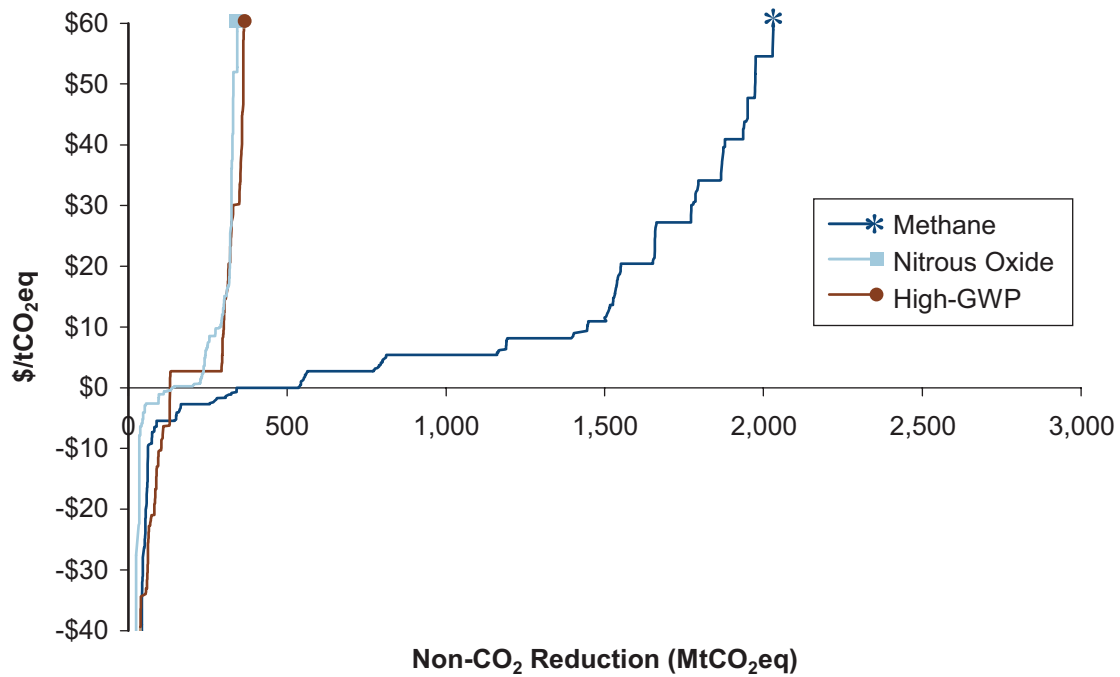
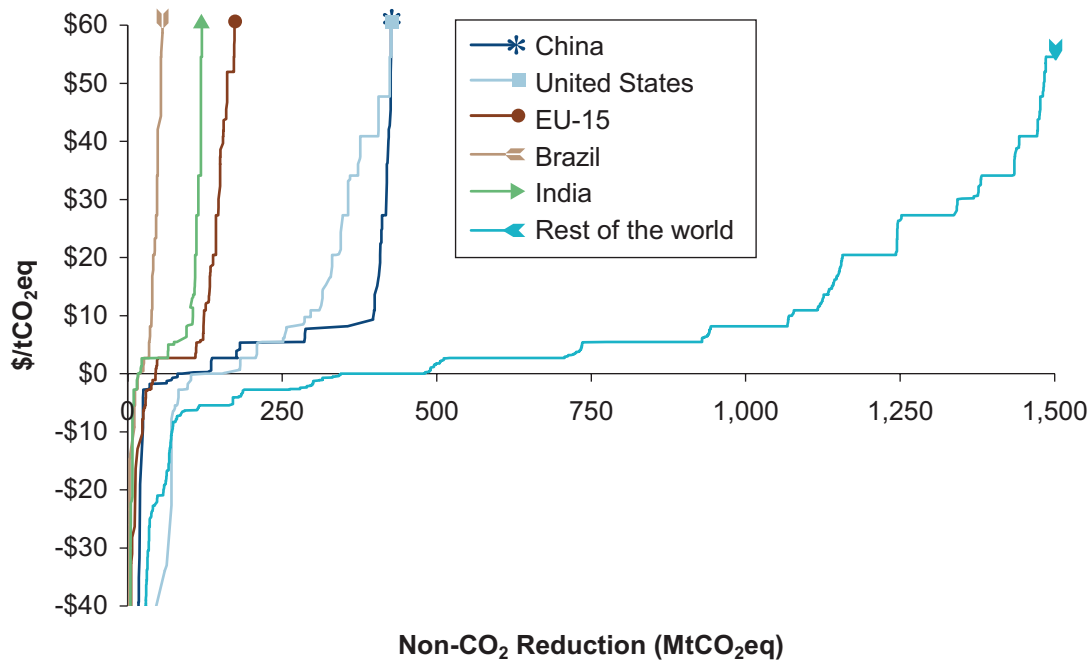


Figure 4-6: Global 2020 MACs by Non-CO₂ Greenhouse Gas Type**Figure 4-7: Global 2020 MACs for Non-CO₂ Greenhouse Gases by Major Emitting Regions**

In the aggregate MACs by gas for the agriculture sector, the net greenhouse gas effects are represented in the aggregate MACs by gas for both CH₄ and N₂O. While mitigating in the livestock and rice sectors affects both N₂O and CH₄ emissions, the dominant effect is on CH₄. Thus, for this analysis, the net effect on CO₂ equivalents is represented in the CH₄ global aggregate MAC. Likewise, cropland soil mitigation affects both N₂O and CH₄ emissions, but the net greenhouse gas effect is represented in the global aggregate N₂O MAC, because N₂O is the dominant mitigation effect.

The 2020 global MACs by major sector (Figure 4-5) illustrate the breakeven mitigation potential for each of the economic sectors. The greatest potential for cost-effective mitigation (i.e. employing mitigation options that are economically feasible in the absence of a carbon price signal), is in the energy and agriculture sectors. In the energy sector, it is estimated that a reduction of approximately 250 MtCO₂eq is possible at a zero-dollar breakeven price. The MACs also show that at higher emissions prices, such as \$20 or \$30 per tCO₂eq, the energy and agriculture sectors show the greatest potential for emissions reduction. The industrial processes and waste sectors also show increased mitigation potential at higher prices, but to a lesser degree. The more vertical slope of the MAC for the industrial sector shows that an increase in the emissions price may not result in any further mitigation beyond a certain point.

Across all non-CO₂ greenhouse gases, methane has the greatest mitigation potential, as shown in the 2020 MACs by greenhouse gas type (Figure 4-6). In the absence of a carbon price signal, methane emissions could be reduced by nearly 500 MtCO₂eq. Nitrous oxide and high-GWP gases also exhibit significant cost-effective mitigation potential, although to a lesser extent than that of methane. As breakeven prices rise, methane potential continues to grow, approaching a reduction potential of 1,800 MtCO₂eq at a breakeven price of \$30/tCO₂eq.

The MACs by major emitting regions (Figure 4-7) exhibit China's large mitigation potential in 2020 at higher breakeven prices. At \$30/tCO₂eq, China could potentially reduce non-CO₂ emissions by up to nearly 450 MtCO₂eq, approximately three times the mitigation potential for the European Union. Both China and the United States exhibit the largest potential for mitigation at higher breakeven prices. India and Brazil also fall in the largest five emitting regions for non-CO₂ greenhouse gases.

The aggregate MACs by economic sector, greenhouse gas type, and region highlight the potential for including non-CO₂ greenhouse gases in multigas strategy analysis. The MACs illustrate that a significant portion of this mitigation potential can be realized at a zero cost and at low carbon prices. This report examines the mitigation potential in each sector in greater detail. Sensitivity analysis on factors such as discount rates, the rate of technical change, and the ratio of domestic to foreign inputs can be found in the sector-specific chapters of this report.

I.5 Limitations and Applications of MACs

While this global mitigation report has important implications for researchers and modelers, it is important to understand not only the limitations of this analysis, but also the potential for misapplication of the data in other analyses.

I.5.1 Limitations and Uncertainties

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

I.5.1.1 Exclusion of Transaction Costs

Future work in the area of mitigation costs will focus on including transactions costs. Current work still in draft by Lawrence Berkeley National Laboratory (LBNL), *Transaction Costs of GHG Emissions Reduction Projects: Preliminary Results* (2003), estimates that transactions costs will add approximately \$1 per ton of carbon to a project. However, the LBNL study is not comprehensive, because it considered only two non-CO₂ projects. Transaction costs are likely to vary significantly, contingent on the size of the project, the applicable mitigation technology, and other factors. Given the lack of comprehensive data, this analysis does not include transaction costs.

I.5.1.2 Static Approach to Abatement Assessment

This analysis does not account for the technological change in such option characteristics as availability, reduction efficiency, applicability, and costs. For example, the same sets of options are applied in 2010 and 2020 and an option's parameters are not changed over its lifetime. This current limitation likely underestimates abatement potential because technologies generally improve over time and costs fall. The introduction of a dynamic approach to assessing regional abatement potentials requires additional assumptions about rates of technological progress and better baseline projections, that, once incorporated into this analysis, will yield a better representation of how MACs change over space and time.

I.5.1.3 Limited Use of Regional Data

The analytic framework used in this study is flexible enough to incorporate regional differences in all the characteristics of abatement options. However, a lack of country-specific data led to a reliance on expert judgment, as noted in the sector-specific chapters. This expert judgment was obtained from source-level technical experts in government and industry with knowledge of project-level technologies, costs, and specific regional conditions. Applicability of abatement options, for example, is reliant on expert judgment, because the makeup of the current infrastructure in a given country in a given sector is uncertain. A much greater use of data originating from local experts and organizations is recommended for the follow-up research of CH₄ abatement in countries outside the United States and EU. Incorporating more regional data could also enhance the range of emissions sources and mitigation options addressed in this analysis.

I.5.1.4 Exclusion of Indirect Emissions Reductions

This analysis does not account for indirect emissions reductions, which can result from either the substitution of electricity from the grid, with electricity produced on-site from recovered CH₄, or from the substitution of natural gas in pipelines with recovered CH₄. Calculation of such indirect reductions requires additional assumptions about the carbon intensity of electricity in different regions. In the U.S. landfill sector, indirect reductions generally augment emissions reductions by about 15 percent. In the agricultural sector, although some mitigation options primarily target a single gas, implementation of the mitigation options will have multiple greenhouse gas effects, most of which are reflected in the agricultural results.

I.5.2 Practical Applications of MACs in Economic Models

MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can also be downloaded in spreadsheet format from our Web site at <<http://www.epa.gov/nonco2/econ-inv/international.html>>.

The MAC data are an important input into the economic modeling of global climate change. The MACs can be applied in a variety of economic models to represent the potential emissions abatement of non-CO₂ greenhouse gases in each sector at a given carbon price.

While the results presented in this report can inform economic models, caution should be taken not to apply the MAC data directly as offset curves. Offset curves are a supply curve of emissions permits that could potentially be available in the market at a given carbon-price environment. However, a price signal alone is not likely to bring about all of the mitigation opportunities available along the MACs presented in this report. Other nonprice factors, such as social acceptance, tend to inhibit mitigation option installation in many sectors. Because of the lack of quantitative data on nonprice factors determining market penetration, we have represented the implied adoption rate of mitigation technologies in our analysis with a mathematical distribution of technologies across the baseline emissions of a sector. Thus, the MACs in our analyses do not represent a supply curve of emissions permits that would be available for purchase, but rather the technical mitigation potential at a given carbon price.

In addition, caution should be taken when applying MACs for sectors that are dependent on energy supply, because of the potential sensitivity of the MACs for these sectors to carbon prices. For example, a positive carbon-price environment may result in reduction in coal use, which may reduce CH₄ emissions. This potential reduction in emissions would have occurred because of a decrease in use of the facility, rather than the installation of a mitigation option in the facility.

This analysis focuses only on the mitigation of non-CO₂, without considering the impacts of CO₂ mitigation. It should be noted that the mitigation potential of non-CO₂ greenhouse gas emissions generated in the energy sector (e.g., coal mining) is inherently tied to the mitigation potential of CO₂ emissions from the same sector. Any modeling of greenhouse gas mitigation in the energy sector should consider the coeffects of any change in energy consumption in both non-CO₂ and CO₂ mitigation potential.

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Section I: Technical Summary Appendixes

Appendixes for this section are available for download from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

II. Energy

Section II presents international emissions baselines and marginal abatement curves (MACs) for energy sources. There are three chapters, each addressing an individual source from the coal mining, natural gas, and oil sectors. These sources are associated with methane (CH_4) emissions. MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can be downloaded in spreadsheet format from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

Section II—Energy chapters are organized as follows:

Methane (CH_4)

II.1 Coal Mining Sector

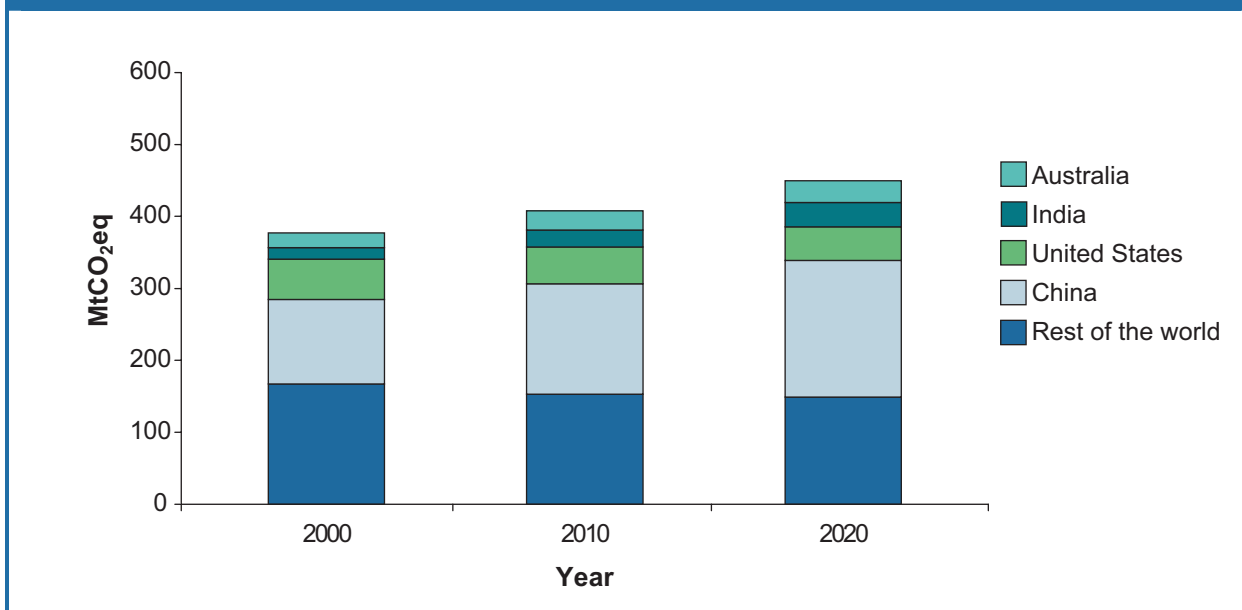
II.2 Natural Gas Sector

II.3 Oil Sector

II.1 Coal Mining Sector

Worldwide, the coal mining industry liberated more than 377 million metric tons of carbon dioxide equivalent (MtCO₂eq), which accounted for 3.3 percent of total anthropogenic methane (CH₄) emissions in 2000. China, the United States, India, and Australia account for more than 56 percent of coal mining CH₄ emissions (Figure 1-1). Emissions are projected to grow 20 percent from 2000 to 2020, with China increasing its share of worldwide emissions from 31 percent to 42 percent.

Figure 1-1: CH₄ Emissions from Coal Mining, by Country: 2000–2020



Source: U.S. Environmental Protection Agency (USEPA), 2006.

II.1.1 Introduction

CH₄ is produced during the process of converting organic matter to coal. The CH₄ is stored in pockets within a coal seam until it is released during coal mining operations. The largest source of emissions occurs during mining. Although, some emissions occur during the processing, transport, and storage of coal. Many factors affect the quantity of CH₄ released, including the gas content of the coal, the permeability and porosity of the coal seams, the method of mining used, and the production capacity of the mining operation. The depth of a coal seam and the type of coal determine the amount of CH₄ present (or the gas content) in and around the coal seams. Deep coal seams generally have large amounts of CH₄ because of greater overburden pressures. As a result, more than 90 percent of fugitive CH₄ emissions from the coal sector come from underground coal mining.

A high concentration of CH₄ in underground coal mines is a safety hazard; the CH₄ must be extracted before mining operations can be undertaken. To maintain low levels of CH₄ in the mine, degasification is employed prior to mining and ventilation air systems are used during mining operations. Traditionally, CH₄ extracted from the mine is released or vented into the atmosphere. Abatement options have been developed to mitigate these emissions.

The three coal mining abatement options addressed in this chapter are (1) degasification, where holes are drilled and CH₄ is captured (not vented) before mining operations begin (or, in the case of gob gas wells, during and after mining operations); (2) enhanced degasification, where advanced drilling technologies are used and captured low-grade gas is purified; and (3) ventilation air methane (VAM) abatement, where low concentrations of CH₄ ventilation air exhaust flows are oxidized to generate heat for process use and/or electricity generation.

The following discussion offers a brief explanation of how CH₄ is emitted from coal mines, followed by a discussion of international baseline emissions for CH₄ from coal mining and projections for future baseline emissions. Then, we characterize possible abatement technologies, outlining their technical specifications, costs and possible benefits, and potential in selected countries. The final section of this chapter discusses emissions reductions that occur following the implementation of each abatement technology and how these reductions are reflected in the marginal abatement curves (MACs).

II.1.2 Baseline Emissions Estimates

Baseline emissions estimates are calculated by developing activity factors and emissions factors per unit of activity. The activity factor for coal mining's level of coal production and the emissions factor are expressed in terms of the quantity of CH₄ release per ton of coal produced.

CH₄ and coal are created through a combination of biological and geological forces, where plant biomass is converted to coal. CH₄ is stored in natural wells and is also diffused inside the coal itself. CH₄ is contained within the coal seam or strata layer by pressure surrounding the seam. When this pressure drops because of natural erosion, faulting, and underground and surface mining, CH₄ emissions occur. CH₄ emissions vary by type of coal mine and type of mining operation. Abandoned mines are also a source of CH₄ emissions.

Underground Mines. The quantity of CH₄ present in a mine is determined significantly by the coal depth. Geologic pressure increases with depth, trapping more CH₄. Coal from underground mines tends to have a higher carbon content, which is associated with a higher CH₄ content.

Ventilation air systems are used in underground mines to maintain low concentration levels of CH₄ during mining operations. CH₄ is combustible at concentrations between 5 percent and 15 percent. As a safety precaution, countries such as the United States require the use of ventilation systems in mines that have any detectable levels of CH₄. Ventilation systems maintain a CH₄ concentration below 1 percent by using large fans to inject fresh air from the surface into the mine, thereby lowering the in-mine CH₄ concentration. This ventilation air is extracted from the mine and vented to the atmosphere through ventilation shafts or bleeder shafts (see explanatory note 1). The vent air contains very low concentrations of CH₄ (typically below 1 percent).

Degasification systems consist of a network of vertical wells drilled from the surface or boreholes drilled within the mine and gathering systems to pull the CH₄ from the wells to the surface. These wells extract large quantities of CH₄ from the coal seam before and after mining operations. CH₄ extracted by degasification systems has higher concentrations (30 percent to 90 percent) than VAM. Concentrations vary depending on the type of coal mined and the degasification technique used.

Surface Mines Surface mining is a technique used to extract coal from shallow depths below the Earth's surface. Because the geologic pressure at shallow depths is much lower, there is insufficient pressure to contain high concentrations of CH₄, so CH₄ content is generally also much lower (see explanatory note 2). As the overlying surface is removed and the coal exposed, CH₄ is emitted directly into the atmosphere. Surface mines contribute only a small fraction of a country's overall emissions, and

surface mining is only applicable in certain geographic regions. For example, in the United States in 2003, surface mining accounted for 67 percent of total domestic coal production. In countries such as China, there is very little surface mining; coal seams are present only at greater depths.

Postmining Operations. The primary source of CH₄ emissions in coal mining is the underground production of coal. However, some emissions occur during processing, storage, and transport of coal. The rate of emissions depends on the type of coal and the way it is handled. The highest rate of emissions occurs when coal is crushed, sized, and dried for industrial and utility uses.

Abandoned Mines. Abandoned mines are another source of CH₄ emissions. Emissions are released through old wells and ventilation shafts. In some cases, the CH₄ from these mines has been captured and used as a source of natural gas or to generate electricity. Currently, these emissions are not included in the baseline estimates.

In summary, the majority of the CH₄ emitted from coal mining comes from gassy underground mines through ventilation and degasification systems. Future emissions levels and the potential for CH₄ recovery and use will be determined by trends in the management of CH₄ gas at such mines.

II.1.2.1 Activity Data

Historical Activity Data

Worldwide coal consumption has increased over time, except in Western Europe, Eastern Europe, and the Former Soviet Union (FSU) (excluding the Russian Federation). Coal consumption decreased 30 percent in Western Europe and 40 percent in Eastern Europe and the FSU from 1990 to 2001. Table 1-1 reports coal mining activity for selected countries during the same period.

In the 1990s, the majority of China's coal mines were operated without modern mining techniques, which usually include cutting equipment, hydraulic pumps, power roof supports, and automated loading devices. In the past decade, in an effort to update their equipment, countries such as China have begun to institute programs to modernize their coal mining operations, allowing them to mine at greater depths. However, several countries experienced decreased demand for coal in the late 1990s, and in response, these countries cut mining production until their surplus supply could be reduced. China dramatically reduced its coal production between 1995 and 2000, and has spent the past 4 years expanding its coal exports to reduce its surplus. Policies and market forces such as these counteract the effects of modernization in mining operations and subsequently increase CH₄ emissions.

Projected Activity Data

Estimated CH₄ emissions baselines are directly related to coal production projections. Sixty percent of the world's recoverable reserves are located in three regions: the United States (25 percent), FSU (23 percent), and China (12 percent) (USEIA, 2003). China is projected to have the largest increase in coal projections because of rapid economic growth; the country is projected to almost double coal consumption by 2025 (USEIA, 2004a).

Table 1-1: Historical Coal Mining Activity Data for Selected Countries (Million Metric Tons)

Country	1990	1995	2000	2001	2002	2003
China	1,190.4	1,537.0	1,314.4	1,458.7	1,521.2	1,635.0
United States	1,029.1	1,033.0	1,073.6	1,127.7	1,094.3	1,069.5
India	247.6	320.6	370.0	385.4	401.1	403.1
Australia	225.8	266.5	338.2	362.9	376.8	373.4
Russian Federation	NA	270.9	264.9	273.4	261.8	294.0
South Africa	193.2	227.3	248.9	250.8	245.8	263.8
Germany	NA	274.2	226.0	227.1	232.6	229.1
Poland	237.1	221.2	179.5	180.3	178.5	177.8
Indonesia	11.6	45.4	84.4	102.0	113.9	132.4
Ukraine	NA	94.6	69.1	68.0	65.6	63.5
Kazakhstan	NA	93.1	81.5	93.0	89.2	86.4
Greece	57.2	63.6	70.4	73.1	77.7	75.3
Canada	75.3	82.7	76.2	77.6	73.3	68.5
Czech Republic	NA	82.6	71.8	72.9	69.8	70.4
Turkey	52.3	60.6	69.6	68.3	58.7	53.1
Rest of the world	1,839.9	370.0	340.9	354.9	355.4	356.4
World Total	5,347.6	5,096.0	4,930.6	5,225.3	5,259.3	5,406.3

Source: Energy Information Administration (USEIA), 2004a.

NA = data unavailable.

Note: Coal production values include anthracite, bituminous, and lignite coal types.

II.1.2.2 Emissions Factors and Related Assumptions

Historical Emissions Factors

Emissions factors for coal mining vary depending on the type of coal being mined, the depth at which the mining face is located, and how much coal is being produced in a given year. In 2000, emissions factors for 56 gassy mines in the United States ranged from 57 to 6,000 million cubic feet of CH₄ per mine annually. Emissions factors for 34 the Russian Federation gassy mines ranged from 17 to 3,200 million cubic feet per mine. For China's 678 state-run mines, emissions factors ranged from 17 to 6,000 million cubic feet per mine annually from coal production. While the range of emissions factors for the United States and China is similar, China has significantly more mines with higher emissions factors. The Intergovernmental Panel on Climate Change (IPCC) estimates average emissions factors by country. Table 1-2 reports emissions factors for selected countries.

Projected Emissions Factors and Related Assumptions

Improvements made in mining technology throughout the last 20 years have resulted in the ability to extract coal from increasingly greater depths. Developing countries' adoption of advanced mining technology has allowed countries such as China and India to reach deeper into their existing coalbed reserves. As discussed earlier, the volume of CH₄ in the coal seam increases at deeper depths because of increasing geological pressure. Thus, CH₄ emissions will rise as technology allows large coal-producing countries to mine deeper.

Table 1-2: IPCC Suggested Underground Emissions Factors for Selected Countries

Country	Emissions Factor (m ³ /ton)	Emissions Factor ^a (tCO ₂ eq/ton)
FSU	17.8–22.2	0.25–0.32
United States	11.0–15.3	0.16–0.22
Germany	22.4	0.32
United Kingdom	15.3	0.22
Poland	6.8–12.0	0.10–0.17
Czechoslovakia	23.9	0.34
Australia	15.6	0.22

Source: IPCC, 1996. Adapted from Reference Manual Table 1-54.

FSU = Former Soviet Union.

^a Conversion factor of 1 m³ = 0.0143 tCO₂eq = 35.31 ft³ × 0.00404 tCO₂eq

II.1.2.3 Emissions Estimates and Related Assumptions

Historical Emissions Estimates

Baseline emissions for Annex I countries are built using publicly available reports produced by the countries themselves. IPCC's *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* methodology was used to estimate emissions in each country, ensuring comparability across countries (IPCC, 1996). The USEPA's baselines assume a "business-as-usual" scenario that does not include climate change mitigation efforts or other national policies that may indirectly reduce the emissions of greenhouse gases.

Table 1-3 reports countries with the largest historical CH₄ baseline emissions for the years 1990, 1995, and 2000. CH₄ emissions declined worldwide between 1990 and 2000 at an average annual rate of about 10 percent.

Table 1-3: Historical Baseline Emissions for Coal Mine CH₄ for Selected Countries (MtCO₂eq)

Country	1990	1995	2000
China	126.1	149.1	117.6
United States	81.9	65.8	56.2
India	10.9	13.7	15.8
Australia	15.8	17.5	19.6
Russian Federation	60.9	36.8	29.0
Ukraine	55.3	30.1	28.3
North Korea	25.3	27.2	26.9
Poland	16.8	15.6	11.9
South Africa	6.7	6.7	7.1
United Kingdom	18.3	12.6	7.0
Germany	25.8	17.6	10.2
Kazakhstan	24.9	17.2	10.0
Colombia	1.9	2.0	3.0
Mexico	1.5	1.8	2.1
Czech Republic	7.6	5.8	5.0
Rest of the world	37.2	32.3	27.1
World Total	516.7	451.5	376.9

Source: USEPA, 2006.

Projected Emissions Estimates

Without the introduction of abatement technologies, worldwide CH₄ emissions from coal mining are projected to increase in the next 20 years. This increase is paralleled by a projected increase in coal consumption over the same period. At the same time, coal's share of overall energy consumption is expected to steadily decrease as a result of technology advances in other energy markets, such as natural gas, and renewed interest in nuclear energy.

Technology adoption and organizational restructuring will improve countries' abilities to produce larger amounts of coal each year. Table 1-4 reports predicted CH₄ baseline emissions for the largest coal-producing countries in the world, assuming the absence of CH₄ abatement technologies.

Table 1-4: Projected Baseline Emissions for Coal Mine CH₄ for Selected Countries (MtCO₂eq)

Country	2005	2010	2015	2020
China	135.7	153.8	171.8	189.9
United States	55.3	51.1	46.4	46.4
India	19.5	23.1	28.4	33.6
Australia	21.8	26.4	28.2	29.7
Russian Federation	26.3	27.5	26.9	26.3
Ukraine	26.3	24.5	23.8	23.2
North Korea	25.6	24.3	23.1	21.9
Poland	11.3	10.8	10.3	9.8
South Africa	7.4	7.2	7.1	7.4
United Kingdom	6.7	6.6	6.4	6.2
Germany	8.4	7.7	7.1	5.9
Kazakhstan	6.7	6.4	6.1	5.8
Colombia	3.4	4.0	4.7	5.5
Mexico	2.5	2.8	3.3	3.7
Czech Republic	4.8	3.9	3.1	3.0
Rest of the world	26.5	27.5	28.9	31.1
World Total	388.1	407.6	425.6	449.5

Source: USEPA, 2006.

II.1.3 Cost of CH₄ Emissions Reductions from Coal Mining

The following is a discussion of the abatement technologies and their costs and benefits.

II.1.3.1 Abatement Option Opportunities

Three abatement opportunities currently available to the coal mining sector are

- degasification,
- enhanced degasification, and
- oxidation of VAM.

Engineering costs for each abatement option are based on representative mine characteristics, such as annual mine production, gassiness of the coal deposits, and CH₄ concentration in ventilation flows. Table 1-5 provides a summary of the one-time investment costs, annual operation and maintenance (O&M) costs, and benefits from using the captured CH₄ as an energy source for each of the three coal mining abatement options included in the analysis.

Table 1-5: Summary of Average Abatement Costs and Benefits for U.S. Coal Mines (in 2000\$)^a

Costs	Average Costs/Benefits (Millions in 2000\$)		
	Degasification	Enhanced Degasification ^b	VAM ^c
One-Time Costs			
Compressor capital	\$1.00	\$0.39	N/A
Gathering line capital	\$0.90	\$0.20	N/A
Processing capital	\$0.04	\$2.56	N/A
Ventilation capital	N/A	N/A	\$18.64
Miscellaneous capital	\$0.38	\$0.14	N/A
Annual Costs			
Drilling capital	\$0.50	\$0.36	N/A
Drilling materials	\$0.94	\$0.31	N/A
Compressors energy (kWh)	\$0.33	\$0.13	N/A
Gathering lines labor	\$0.25	\$0.96	N/A
Processing materials	\$0.13	\$0.18	N/A
Ventilation operating costs	N/A	N/A	\$0.91
Miscellaneous labor	\$0.28	\$0.12	N/A
Annual After-Tax Benefits			
CH ₄ sold or purchases offset	\$0.97	\$0.34	\$2.78
Depreciation Tax Benefits			
	\$0.02	\$0.24	\$0.14

Source: Gallaher and Delhotal, 2005.

N/A = Not applicable.

^a Based on a population of 57 U.S. coal mines, accounting for 75 percent of the total liberated CH₄ from U.S. coal production.

^b Incremental costs and benefits in addition to degasification (Option 1).

^c Underlying VAM costs are from Delhotal et al. (2005).

Degasification and Pipeline Injection

High-quality CH₄ is recovered from coal seams by drilling vertical wells up to 10 years in advance of a mining operation or drilling horizontal boreholes up to 1 year before mining. Most mine operators exercise just-in-time management of gate road development; subsequently, horizontal cross-panel boreholes are installed and drain gas for 6 months or less. Long horizontal boreholes are used by only a few operators in the United States and Australia.

In some cases, high-quality CH₄ also can be obtained from gob wells. Gob gas CH₄ concentrations can range from 50 percent to over 90 percent (USEPA, 1999). The gas recovered is injected into a natural gas pipeline requiring virtually no purification in the initial stages of production, but necessitating treatment over time to upgrade the gas to pipeline quality. Gob gas sales from a given location typically decline over time because of declining levels of concentration. In the United States, of the CH₄ recovered from degasification (or gas drainage as it is often called) 57 percent can be directly used for pipeline injection (USEPA, 1999).

Cost Analysis

- **Capital Costs.** Capital costs include the one-time (upfront) costs of purchasing compressors, gathering lines, dehydrators, and other miscellaneous capital such as safety equipment and licenses. Table B-6 in Appendix B for this chapter offers a detailed description of the factors that determine the required number of each capital component by mine.
- **Annual Costs.** These costs include materials and labor for drilling, moving gathering lines, and maintaining the dehydrators. Drilling capital is also considered an annual cost because drilling is conducted annually. Annual costs generally increase or decrease proportionally to the volume of CH₄ liberated at the individual mine. Table B-6 offers a detailed description of the factors that determine these costs.
- **Cost Savings.** Cost savings result from the capture and reuse of natural gas. For basic degasification, it is assumed that 57 percent of gas capture is suitable for injection into the natural gas pipelines and hence can be sold directly into the system (USEPA, 1999).

Enhanced Degasification and Pipeline Injection

In enhanced degasification, CH₄ is recovered in the same way as in degasification, using vertical wells, horizontal boreholes, and gob wells. In addition, the mine invests in enrichment technologies such as nitrogen removal units (NRUs) and dehydrators, used primarily to enhance medium-quality gob well gas by removing impurities, allowing for larger quantities of CH₄ to be captured and used. This option also assumes tighter well spacing to increase recovery. The enrichment process and tighter spacing improve recovery efficiency 20 percent more than the first option discussed above (USEPA, 1999). All costs and benefits presented in Table 1-5 for enhanced degasification are incremental in that they represent additional abatement costs and CH₄ sales above and beyond the basic degasification.

Cost Analysis

- **Capital Costs.** Enhanced degasification requires the same capital equipment as the degasification option. In addition, the enhanced option requires an NRU with an estimated average cost of \$200,000 per unit.
- **Annual Costs.** Similar to degasification, enhanced degasification's annual costs include materials and labor for drilling, moving gathering lines, and maintaining the dehydrators. However, annual drilling costs are higher for enhanced degasification because the wells are drilled at closer intervals to one another. Costs vary proportionally to the amount of gas liberated.
- **Cost Savings.** It is assumed that 77 percent of the CH₄ captured as part of enhanced degasification can be injected into the natural gas pipeline system. There is a 21 percent increase over the basic degasification mitigation option (incremental benefits) because gas processing equipment facilitates nitrogen removal.

Oxidation of Ventilation Air Methane

Oxidation technologies (both thermal and catalytic) have the potential to use CH₄ emitted from coal mine ventilation air. It is not economically feasible to sell this gas to a pipeline because of its extremely low CH₄ concentration levels (typically below 1 percent). However, VAM can be oxidized to generate CO₂ and heat, which in turn may be used directly to heat water or to generate electricity. If oxidizer technology were applied to all mine ventilation air with concentrations greater than 0.15 percent CH₄, approximately 97 percent of the CH₄ from the ventilation air could be mitigated.

Cost Analysis

- **Capital Costs.** Capital costs for VAM oxidation are a function of the level of CH₄ concentration in the ventilation air and the ventilation air flow rate.
- **Annual Costs.** Annual costs consist primarily of the labor and electricity costs associated with running the oxidizer. Both of these are proportional to coal production.
- **Cost Savings.** Heat generated by oxidation systems can be used to heat water (e.g., for steam or district heating applications) or to generate electricity.

II.1.4 Results

This section presents the Energy Modeling Forum (EMF) Working Group 21 study's MAC analysis results in tabular format.

II.1.4.1 Data Tables and Graphs

Table 1-6 presents the average breakeven price and the reduction in absolute and percentage terms for the mitigation options discussed in Section II.1.3.1.

Table 1-6: Summary of Coal Mining Abatement Options Included in the Analysis

Technology	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (%) from baseline)	Emissions Reduction in 2010 (MtCO ₂ eq)	Emissions Reduction in 2020 (MtCO ₂ eq)
Assuming a 10% discount rate and a 40% tax rate				
Degasification and pipeline injection	–\$11.66	28%	0.55	0.55
Enhanced degasification, gas enrichment, and pipeline injection	\$2.40	10%	0.19	0.19
Catalytic oxidation ^a (United States)	\$14.36	24%	0.77	0.94
Flaring	\$2.47	1%	0.03	0.03
Degasification and power production—A	–\$2.09	5%	0.04	0.03
Degasification and power production—B	\$5.68	9%	0.06	0.06
Degasification and power production—C	\$19.80	28%	0.70	0.83
Catalytic oxidation (EU-15)	\$11.34	18%	0.13	0.11

Source: USEPA, 2003. Adapted from Coal Sector technology tables in Appendix B of EMF report.

EU-15 = European Union.

Note: Some technologies are not present in all countries. See source for the individual technology's presence in various countries.

^a Catalytic oxidation is considered a VAM technology.

The EMF regional baselines and MAC results of the EMF-21 study are presented in Tables 1-7 and 1-8 for 2010 and 2020 using the base energy price, a 10 percent discount rate, and a 40 percent tax rate. These MACs represent percentage reductions in baseline emissions for individual regions/countries at selected breakeven prices. Figure 1-2 provides MACs for the five EMF countries/regions with the largest estimated emissions from coal mining in 2020.

The MACs presented in this section represent static abatement curves using breakeven prices built on the assumption of fixed mitigation cost and aggregate countrywide natural gas statistics. Appendix B presents more recent efforts to develop an alternative framework for conducting MAC analysis that addresses the limitations of the EMF-21 MAC analysis.

Table 1-7: Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	9.3	8.2	8.7
Annex I	181.9	173.5	165.8
Australia/New Zealand	20.0	26.8	30.3
Brazil	1.3	1.1	1.0
China	117.6	153.8	189.9
Eastern Europe	24.3	23.4	24.1
EU-15	22.5	19.6	17.0
India	15.8	23.1	33.6
Japan	0.8	0.7	0.7
Mexico	2.1	2.8	3.7
Non-OECD Annex I	61.7	56.8	54.7
OECD	123.5	120.2	115.3
Russian Federation	29.0	27.5	26.3
South & SE Asia	31.7	29.8	28.4
United States	56.2	51.1	46.4
World Total	376.9	407.6	449.5

Source: USEPA, 2006.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

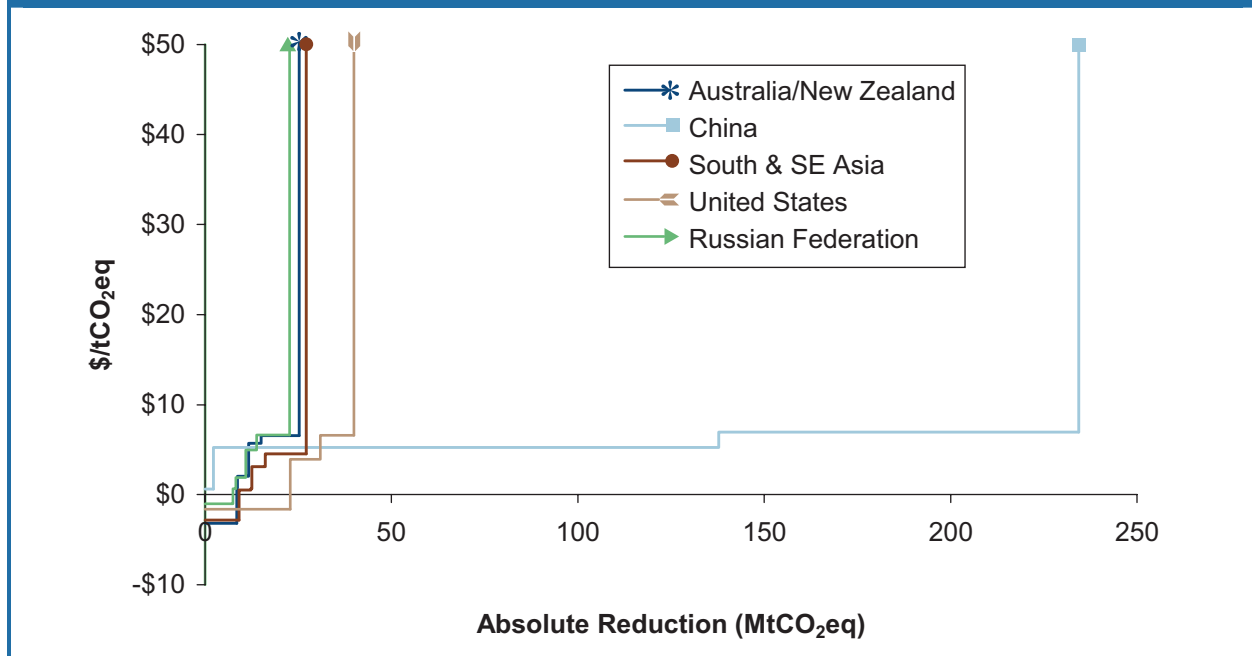
Note: World Total does not equal the sum of the countries listed in this table because the regional groupings are a subset of the full EMF regional grouping list. See Appendix A of this report for the full EMF list of countries by region.

Table 1-8: Coal Mining MACs for Countries Included in the Analysis

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	38.50%	85.53%	85.53%	85.53%	85.53%	38.50%	85.53%	85.53%	85.53%	85.53%
Annex I	34.81%	78.05%	78.05%	78.05%	78.05%	36.33%	81.45%	81.45%	81.45%	81.45%
Australia/New Zealand	27.91%	83.05%	83.05%	83.05%	83.05%	27.91%	83.05%	83.05%	83.05%	83.05%
Brazil	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
China	0.00%	84.45%	84.45%	84.45%	84.45%	0.00%	84.45%	84.45%	84.45%	84.45%
Eastern Europe	34.16%	73.23%	73.23%	73.23%	73.23%	34.16%	73.23%	73.23%	73.23%	73.23%
EU-15	0.00%	41.11%	41.11%	41.11%	41.11%	0.00%	41.11%	41.11%	41.11%	41.11%
India	0.00%	84.18%	84.18%	84.18%	84.18%	0.00%	84.18%	84.18%	84.18%	84.18%
Japan	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%	98.00%
Mexico	28.50%	85.53%	85.53%	85.53%	85.53%	28.50%	85.53%	85.53%	85.53%	85.53%
Non-OECD Annex I	32.10%	84.80%	84.80%	84.80%	84.80%	39.21%	103.58%	103.58%	103.58%	103.58%
OECD	35.40%	75.22%	75.22%	75.22%	75.22%	34.95%	74.26%	74.26%	74.26%	74.26%
Russian Federation	27.65%	84.29%	84.29%	84.29%	84.29%	27.65%	84.29%	84.29%	84.29%	84.29%
South & SE Asia	28.15%	84.09%	84.09%	84.09%	84.09%	28.15%	84.09%	84.09%	84.09%	84.09%
United States	49.22%	85.97%	85.97%	85.97%	85.97%	49.22%	85.97%	85.97%	85.97%	85.97%
World Total	16.66%	79.84%	79.84%	79.84%	79.84%	14.51%	79.81%	79.81%	79.81%	79.81%

Source: USEPA, 2003.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 1-2: EMF MACs for Top Five Emitting Countries/Regions from Coal: 2020

Source: USEPA, 2003.

Note: Regional MACs were constructed using percentage reductions from USEPA (2003), with baselines from USEPA (2005).

II.1.4.2 Uncertainties and Limitations

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

- Accurate Distribution of Mine Type for Each Country.** Extrapolating from available information about individual mines to project fugitive emissions at a national level implies that the available data are representative of the country's coal production not already included in the existing database. A more accurate distribution of representative mines would improve the accuracy of the cost estimates and the shape of each MAC. These data would include mines of all sizes, emissions factors, and production levels. This lack of information becomes increasingly problematic when evaluating a country such as China, where the majority of mines are small, private mines that are not represented in currently available data sources.
- Country-Specific Tax and Discount Rates.** In this analysis, a single tax rate is applied to mines in all countries to calculate the annual benefits of each technology. In reality, however, tax rates vary across countries, and in the case of state-run mines in China, taxes may not even be applicable. Similarly, the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately quantify benefits and breakeven prices.
- Improved Information on Public Infrastructure.** A more detailed understanding of each country's natural gas infrastructure would improve the estimates of costs associated with transporting CH₄ from a coal mine to the pipeline. Countries with little infrastructure will have a much higher transportation cost associated with degasification and enhanced degasification technologies.

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

II.1.5 Summary

The methodology and data discussed in this section describe the MAC analysis conducted for the coal mining sector by the EMF-21 study. MACs for 2010 and 2020 were estimated based on aggregated industry data from each country or region. The MACs represent static estimates of potential CH₄ mitigation from coal mines based on available information regarding infrastructure and country-reported emissions estimates provided through the United Nation's Framework Convention on Climate Change emissions inventory reports.

II.1.6 References

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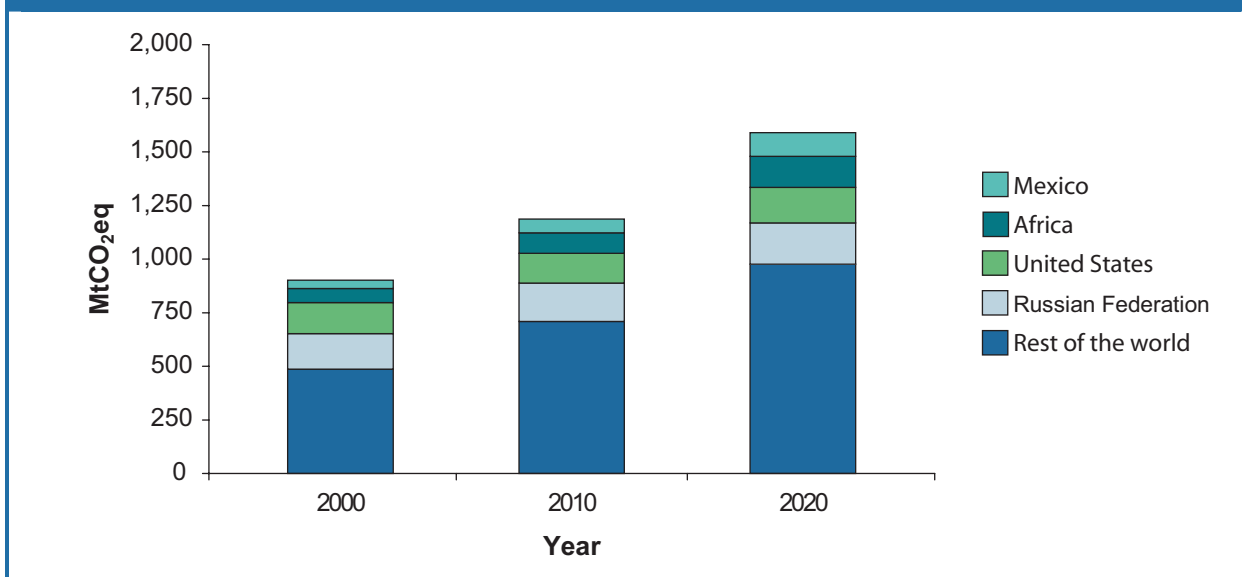
Explanatory Notes

1. Bleeder shafts are currently used in only a limited number of countries, including the United States and the Russian Federation.
2. There are exceptions. In Kazakhstan, for example, the surface mines in Ekibastuz are very gassy and prone to outbursts; this is the rare exception, though.

II.2 Natural Gas Sector

Natural gas systems are a leading source of anthropogenic CH₄ emissions, accounting for more than 970 MtCO₂eq (USEPA, 2006). The USEPA estimates that natural gas systems account for 8 percent of total global CH₄ emissions. The Russian Federation, the United States, Africa, and Mexico account for more than 43 percent of the world's CH₄ emissions in the natural gas sector (USEPA, 2006) (Figure 2-1).

Figure 2-1: CH₄ from Natural Gas Systems by Country: 2000–2020



Source: USEPA, 2006.

Emissions are projected to increase 54 percent from 2005 to 2020, with Brazil and China having the largest growth of 737 percent and 611 percent, respectively (USEPA, 2006). The two regions projected to experience the largest growth in production are the Middle East and the developing countries of Latin America.

II.2.1 Introduction

Natural gas systems include the production, processing, transportation and storage, and distribution of natural gas. Table 2-1 identifies facilities and equipment associated with different segments of the natural gas system.

During production, gas exit swells under pressure greater than 1,000 pounds per square inch (psi). The gas is routed through dehydrators, where water and other liquids are removed, and then to small-diameter gathering lines for transport to either processing plants or injection directly into transmission or distribution pipelines. Processing plants further purify the gas by removing natural gas liquids, sulfur compounds, particulates, and CO₂. Impurities in the gas are extracted through a cooling process that forces the impurities to condense into a liquid, which is then vaporized in a reboiler and vented into the atmosphere.

Table 2-1: Natural Gas Industry Characterization

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

Source: USEPA, 1996.

Processed gas, which is 95 percent CH₄, is then injected into large-diameter transmission pipelines, where it is compressed and transported to storage and distribution facilities. Storage stations are either above- or belowground facilities and include compressor stations. Distribution companies reduce high-pressure gas (averaging 300 psi to 600 psi) to pounds or even ounces per square inch for delivery to homes, businesses, and industries.

CH₄ emissions occur from normal operations in each of the four segments of the natural gas industry. Equipment/pipeline leaks and venting activities are the primary sources of CH₄ emissions in the natural gas sector (USEPA, 1996). As the gas moves through system components under extreme pressure, CH₄ can escape to the atmosphere through worn valves, flanges, pump seals, compressor seals, and joints or connections in gathering pipelines. For example, in the production segment of the natural gas system, emissions occur at the wellhead, during dehydration, and when the gas is compressed to be transported from the wellhead site to a processing plant. CH₄ emissions also occur during routine maintenance throughout the natural gas system. For example, emissions from the transmission segment include intentional blowdown or purge activities during maintenance and inspection.

Abatement options for the natural gas sector generally fall into three categories: equipment changes/upgrades, changes in operational practices, and direct inspection and maintenance (DI&M). Many abatement options are applicable across all four segments of the natural gas system described in Table 2-1.

- Natural gas emissions from pneumatic control devices are one of the largest sources of CH₄ emissions in the natural gas industry. Substituting compressed air for pressurized natural gas throughout the natural gas system eliminates the constant bleed of natural gas to the atmosphere.
- Changing operational practices, such as using pumpdown techniques to remove product (i.e., natural gas) from sections of pipeline and the compressor during maintenance and repair, reduces the volume of natural gas vented to the atmosphere when components are taken offline.
- Implementing DI&M programs can eliminate as much as 80 percent of fugitive CH₄ emissions that result from equipment and pipeline leaks throughout the system.

The following sections discuss the activity data and emissions factors used to develop baseline emissions, abatement options and their costs, and CH₄ MACs for natural gas systems for selected countries. The chapter concludes with sensitivity analyses on key assumptions and a discussion of uncertainties and limitations.

II.2.2 Baseline Emissions Estimates

Annual emissions baselines for natural gas systems are calculated using activity factors, activity factor drivers, and emissions factors. Each of these factors can be affected by variations in individual countries' production process techniques, the intensity of maintenance schedules, and the age of the natural gas system. Table C-7 (see Appendix C) lists the activity factors, emissions factors, and emissions for sources in the United States.

II.2.2.1 Activity Data

Activity factors and activity factor drivers are used to estimate the population of equipment in each segment of the natural gas system.

Activity Factors

Activity factors include both the physical number of units and the level of operation/activity of these units. These factors inform the underlying population for each type of equipment present in a natural gas system. Examples of activity factors include the number of compressors in the production segment, the throughput across segments, miles of pipeline, number of blowdowns, and the total number of gas wells. Activity factors are used in conjunction with emissions factors (discussed below) to calculate annual baseline emissions. This report uses activity factors used to characterize the U.S. natural gas system in 1992 (USEPA, 1996).

Activity Factor Drivers

Activity factor drivers are used to adjust the activity factors from 1992 to reflect changes over time or differences between countries. The primary drivers are changes in production and consumption levels, but drivers can also include changes in the age or underlying technology of natural gas systems. Activity factor drivers determine how the equipment population numbers fluctuate in response to expanding or contracting natural gas markets. For example, the number of dehydrators in a natural gas system is determined by the number of wells, which is driven by production levels. If production of natural gas drops, the number of wells required decreases. This drives down the number of dehydrators in operation (or the operating capacity of dehydrators in place), reducing the baseline emissions estimate.

Historical Activity Data

Historically, natural gas has been produced by developed countries, which have the technology base and capital available to facilitate the development of natural gas industries. In 2001, the FSU and the United States accounted for 33 percent of the world's natural gas production (91.1 trillion cubic feet) (USEIA, 2005a). Table 2-2 reports natural gas production by country and region for 1980 through 2003.

During the past 20 years, natural gas consumption has increased (see Table 2-3). Developing countries have experienced the largest increase in consumption in recent years, while industrialized countries have experienced small but steady growth over the same period. Currently, developing countries consume significantly less natural gas than developed countries; however, this trend is projected to change in the next 5 to 10 years.

Table 2-2: Natural Gas Production by Country and Region: 1980–2003 (Trillion Cubic Feet)

Country/Region	1980	1990	1995	2000	2001	2002	2003
Canada	2.76	3.85	5.60	6.47	6.60	6.63	6.45
Mexico	0.90	0.90	0.96	1.31	1.30	1.33	1.49
United States	19.40	17.81	18.60	19.18	19.62	18.93	19.04
North America	23.06	22.56	25.16	26.97	27.51	26.89	26.98
Antarctica	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Central and South America	1.23	2.01	2.58	3.43	3.65	3.72	4.20
Netherlands	3.40	2.69	2.98	2.56	2.75	2.66	2.58
Norway	0.92	0.98	1.08	1.87	1.95	2.41	2.59
United Kingdom	1.32	1.75	2.67	3.83	3.69	3.61	3.63
Western Europe	7.46	7.24	8.80	10.19	10.27	10.55	10.62
Russian Federation	NA	NA	21.01	20.63	20.51	21.03	21.77
Turkmenistan	NA	NA	1.14	1.64	1.70	1.89	2.08
Uzbekistan	NA	NA	1.70	1.99	2.23	2.04	2.03
Eastern Europe and FSU	17.06	30.13	25.93	26.22	26.48	27.05	28.00
Iran	0.25	0.84	1.25	2.13	2.33	2.65	2.79
Saudi Arabia	0.33	1.08	1.34	1.76	1.90	2.00	2.12
United Arab Emirates	0.20	0.78	1.11	1.36	1.39	1.53	1.58
Middle East	1.42	3.72	4.99	7.57	7.98	8.67	9.12
Algeria	0.41	1.79	2.05	2.94	2.79	2.80	2.91
Africa	0.69	2.46	3.01	4.44	4.63	4.74	5.07
Indonesia	0.63	1.53	2.24	2.36	2.34	2.48	2.62
Malaysia	0.06	0.65	1.02	1.50	1.66	1.71	1.89
Asia and Oceania	2.44	5.44	7.50	9.48	9.92	10.53	11.19
World Total	53.35	73.57	77.96	88.29	90.45	92.15	95.18

Source: USEIA, 2005b.

FSU = Former Soviet Union; NA = Data unavailable.

Projected Activity Data

Production and consumption of natural gas are expected to increase in the near term, with developing countries experiencing the largest percentage increases over the next 20 years. Table 2-4 and Table 2-5 list projected natural gas production and consumption, respectively, by selected country and region from 2010 to 2025. Annual growth in production in Central and South America and Africa is expected to approach 5 percent. However, the United States, Eastern Europe, and the FSU are still projected to account for more than 50 percent of world natural gas production in 2025 (USEIA, 2004).

Natural gas is projected to be the fastest growing source of primary energy over the next 20 years. Consumption is expected to increase by more than 70 percent (average annual rate of 2.2 percent) from 2001 to 2025 (USEIA, 2005a). Developing countries will continue to experience the largest percentage increases in demand.

Table 2-3: Natural Gas Consumption by Country and Region: 1980–2003 (Trillion Cubic Feet)

Country/Region	1980	1990	1995	2000	2001	2002	2003
Canada	1.88	2.38	2.79	2.95	2.91	3.06	3.21
Mexico	0.80	0.92	1.04	1.40	1.40	1.50	1.82
United States	19.88	19.17	22.21	23.33	22.24	23.01	22.38
North America	22.56	22.47	26.04	27.68	26.55	27.57	27.41
Central and South America	1.24	2.02	2.58	3.30	3.54	3.56	3.82
France	0.98	1.00	1.18	1.40	1.47	1.59	1.54
Germany	NA	NA	3.17	3.10	3.24	3.20	3.32
Italy	0.97	1.67	1.92	2.50	2.51	2.49	2.72
Netherlands	1.49	1.54	1.70	1.73	1.77	1.76	1.78
United Kingdom	1.70	2.06	2.69	3.37	3.34	3.31	3.36
Western Europe	8.66	10.50	12.76	15.13	15.51	15.87	16.43
Russian Federation	NA	NA	14.51	14.13	14.41	14.57	15.29
Ukraine	NA	NA	2.97	2.78	2.62	2.78	3.02
Uzbekistan	NA	NA	1.35	1.51	1.60	1.64	1.67
Eastern Europe and FSU	15.86	27.83	23.04	22.80	23.30	23.68	24.97
Iran	0.23	0.84	1.24	2.22	2.48	2.80	2.79
Saudi Arabia	0.33	1.08	1.34	1.76	1.90	2.00	2.12
United Arab Emirates	0.11	0.66	0.88	1.11	1.15	1.29	1.34
Middle East	1.31	3.60	4.74	6.82	7.05	7.63	7.86
Africa	0.74	1.35	1.69	2.04	2.28	2.45	2.55
China	0.51	0.49	0.58	0.93	1.05	1.13	1.18
Indonesia	0.20	0.55	1.06	1.08	1.18	1.20	1.23
Japan	0.90	1.85	2.21	2.84	2.84	2.94	3.05
Asia and Oceania	2.52	5.61	7.79	10.43	11.08	11.76	12.46
World Total	52.89	73.37	78.64	88.21	89.31	92.51	95.50

Source: USEIA, 2005b.

FSU = Former Soviet Union; NA = Data unavailable.

II.2.2.2 Emissions Factors and Related Assumptions

Emissions factors in the natural gas sector are defined as the rate of CH₄ emissions from a facility or piece of equipment or from normal operations and routine maintenance. Estimated emissions factors are used in conjunction with activity factors and activity factor drivers to generate baseline emissions estimates by country. Table 2-6 reports estimated emissions factors by country, provided by IPCC's *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*. These emissions factors represent the average estimated emissions factor across all segments of the natural gas system.

The system-level emissions factors in Table 2-6 are used to calculate country-specific baseline emissions (see Section II.2.2.3) for countries outside the United States. For the United States, a more detailed set of emissions factors is used to calculate baseline emissions. Appendix Table C-7 presents the individual facility and equipment emissions factors estimated for the U.S. natural gas system, adapted from the USEPA report *Methane Emissions from the Natural Gas Industry* (USEPA, 1996).

This section discusses the source of the emissions factors used to develop country-specific baseline emissions.

Table 2-4: Projected Natural Gas Production by Country and Region: 2010–2025 (Trillion Cubic Feet)

Country/Region	2010	2015	2020	2025	Average Annual Percentage Change, 2001–2025
Canada	7.6	7.5	7.1	7.5	0.5
Mexico	1.5	1.6	1.9	2.1	2.0
United States	20.5	21.6	23.8	24.0	0.8
North America	29.6	30.6	32.8	33.6	0.8
Central and South America	5.5	7.1	8.6	10.6	4.6
Western Europe	9.0	9.0	8.9	9.8	–0.2
Eastern Europe and FSU	31.0	35.7	40.4	45.3	2.2
Middle East	9.8	12.1	15.6	18.8	3.5
Africa	8.1	9.9	11.9	14.1	4.8
China	1.6	1.9	2.3	3.1	4.5
Asia	12.5	14.2	16.3	18.8	2.6
World Total	105.5	118.5	134.5	151.0	2.1

Source: USEIA, 2004.

FSU = Former Soviet Union.

Table 2-5: Projected Natural Gas Consumption by Country and Region: 2010–2025 (Trillion Cubic Feet)

Country/Region	2010	2015	2020	2025	Average Annual Percentage Change, 2001–2025
Canada	3.9	4.3	4.6	4.7	2.0
Mexico	1.8	2.2	2.6	3.0	3.0
United States	25.6	28.3	30.4	30.9	1.3
North America	31.3	34.8	37.6	38.6	1.5
Brazil	0.9	1.3	1.7	2.1	6.8
Other Central/South America	3.8	4.3	4.8	5.4	2.4
Western Europe	17.3	19.0	20.4	22.4	1.8
Russian Federation	16.2	17.9	19.5	20.7	1.5
Eastern Europe	4.0	4.6	5.2	5.8	3.5
FSU	25.6	29.0	31.0	33.3	2.0
Middle East	10.6	12.6	14.5	16.6	3.1
Africa	3.1	4.1	4.9	6.0	4.0
China	2.6	3.4	4.2	6.5	7.8
Emerging Asia	10.6	13.3	16.3	20.7	4.3
World Total	111.4	127.9	141.6	156.2	2.3

Source: USEIA, 2005c.

FSU = Former Soviet Union.

Table 2-6: IPCC Estimated Emissions Factors from Natural Gas by Region

Country/Region	Emissions Factors by Industry Segment (kg/petajoule)	
	Production	Consumption
Eastern Europe/FSU ^a	392,800	527,900
Other oil-exporting countries ^b	67,795	228,310
United States and Canada	71,905	88,135
Western Europe ^c	20,900	84,500
Rest of the world ^d	67,795	228,310

Source: IPCC, 1996. Adapted from Reference Manual Tables 1-60, 1-61, 1-62, 1-63, and 1-64.

FSU = Former Soviet Union

^a Includes Albania, Bulgaria, Czech and Slovak Republics, Hungary, Poland, Romania, and the former Yugoslavia.

^b Includes Algeria, Nigeria, Venezuela, Indonesia, Iran, Iraq, Kuwait, Saudi Arabia, United Arab Emirates, Ecuador, and Mexico.

^c Includes Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

^d Includes Asia, Africa, Middle East, Oceania, and Latin America.

Historical Emissions Factors

The United States conducted a study to measure and estimate emissions factors for all components in its national infrastructure (USEPA, 1996). This study measured or estimated emissions factors for more than 100 pieces of natural gas equipment, such as gas wells, compressors, pipeline, and system upsets. The study was conducted in 1992, and the emissions factors were revised and published in 1996. Table C-7 (see Appendix C) lists the study's emissions factors by component and segment of the infrastructure. These emissions factors are used to calculate the U.S. baseline emissions estimate (see Table 2-7). For all other countries, IPCC systems emissions factors (Table 2-6) were used to develop baseline emissions estimates.

Table 2-7: Baseline Emissions for Natural Gas Systems for Selected Countries: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
Russian Federation	334.3	240.6	165.3
United States	143.9	148.0	145.7
Iran	19.4	29.1	34.6
Mexico	22.7	25.3	37.4
Ukraine	78.3	81.8	86.9
Turkmenistan	19.5	16.7	24.3
Nigeria	12.5	17.6	37.8
Venezuela	29.8	34.8	37.7
Turkey	19.9	28.5	38.7
India	8.0	12.5	15.8
United Arab Emirates	18.9	26.7	33.2
Uzbekistan	27.2	30.3	34.8
Indonesia	31.3	41.4	42.1
Canada	25.4	34.3	37.3
Argentina	8.0	10.9	14.9
Rest of the world	132.0	145.3	186.0
World Total	931.0	923.8	972.4

Source: USEPA, 2006.

Projected Emissions Factors and Related Assumptions

Over time, the USEPA estimates that the proportional growth in baseline CH₄ globally will slow relative to the growth in overall production and consumption. Emissions factors in mature natural gas systems are projected to increase because of equipment age and fatigue. However, this increase will be counterbalanced by rapidly expanding industries in developing countries that will employ state-of-the-art technology when constructing natural gas infrastructures.

For example, China is in the early stages of developing a natural gas infrastructure. China's use of state-of-the-art technology supplied by the United States, the European Union (EU), and Japan will result in low emissions factors, and these low emissions factors will constrain the growth in China's national baseline emissions over time.

II.2.2.3 Emissions Estimates and Related Assumptions

The USEPA estimates the emissions contribution of each segment in the natural gas system by multiplying emissions factors (EF) by associated activity factors (AF) and then summing them, as shown below:

$$\begin{aligned} \text{Country Total Emissions} = & \text{Production (EF} \times \text{AF)} + \text{Processing (EF} \times \text{AF)} + \\ & \text{Transport (EF} \times \text{AF)} + \text{Storage (EF} \times \text{AF)} + \\ & \text{Distribution (EF} \times \text{AF)} \end{aligned} \quad (2.1)$$

From Equation (2.1), individual country baseline estimates using natural gas production and consumption data are coupled with the IPCC system emissions factors presented in Table 2-6. This section discusses the historical and projected changes in the baseline emissions estimates.

Historical Emissions Estimates

Baseline emissions are built using publicly available reports produced by the countries themselves. IPCC guidelines and methods were used to estimate emissions in each country, ensuring comparability across countries. Table 2-7 presents the countries with the largest historical CH₄ baseline emissions for 1990, 1995, and 2000. CH₄ emissions increased worldwide from 1990 to 2000 at an average annual rate of 3 percent.

Projected Emissions Estimates

Overall, world CH₄ emissions are expected to increase during the next 20 years at an average annual rate of 5.7 percent (USEPA, 2003a), reflecting a projected increase in natural gas use as a share of total energy consumption. Table 2-8 presents the predicted CH₄ baseline emissions for the largest emitting countries in the global natural gas sector. Developing countries will experience the largest percentage increases in emissions, which closely parallel expected increases in consumption and production of natural gas. However, the level of technology employed in building new infrastructure will help constrain baseline emissions for these countries.

Table 2-8: Projected Baseline Emissions for Natural Gas Systems for Selected Countries: 2005–2020
(MtCO₂eq)

Country	2005	2010	2015	2020
Russian Federation	171.9	178.6	185.8	193.1
United States	124.3	138.6	151.0	164.8
Iran	56.8	74.0	96.4	125.3
Mexico	49.5	64.0	82.6	111.4
Ukraine	90.4	93.9	97.7	101.5
Turkmenistan	46.2	72.1	83.2	93.9
Nigeria	49.1	59.2	73.3	89.4
Venezuela	45.2	50.7	63.0	84.8
Turkey	50.2	56.6	62.9	75.5
India	25.8	35.7	49.5	61.4
United Arab Emirates	38.7	47.4	52.8	59.7
Uzbekistan	39.6	44.3	45.4	46.8
Indonesia	46.8	48.0	46.3	45.2
Canada	37.3	38.2	39.8	41.1
Argentina	14.9	16.7	20.9	28.1
Rest of the world	213.8	253.4	313.0	373.8
World Total	1,100.4	1,271.5	1,463.7	1,695.8

Source: USEPA, 2006.

II.2.3 Cost of CH₄ Emissions Reductions from Natural Gas Systems

Capital costs, annual costs, and annual benefits for individual abatement options are obtained from the USEPA's economic cost model. The economic cost model incorporates activity and emissions factors published by the USEPA and the Gas Research Institute (GRI) (USEPA, 1996). The USEPA's economic cost model reports one-time capital costs, annual operating costs, and reduction efficiencies for 118 different abatement options applied across the four sectors: production, processing, transmission and storage, and distribution. Options range from upgrading compressors and pipes to enhancing inspection and detection techniques. The number of options by sector is presented in Table 2-9. Table C-8 (in Appendix C) contains a brief description of the major categories of natural gas abatement options.

It should be noted that a large number of abatement options for the natural gas sector are substitutes for each other. Thus, there may be several options for reducing emissions for a particular piece of equipment, but only one may be selected. For example, DI&M of gas wells is substitutable with enhanced DI&M. In developing the MACs, the model chooses between substitute options, selecting the option with the lowest breakeven price.

Table 2-9: Prevalence of Abatement Options by Infrastructure Component

Infrastructure Component	Total
Production	39
Processing	2
Transmission and storage	51
Distribution	26

Source: USEPA, 2000.

II.2.3.1 Abatement Option Opportunities

This section presents a general overview of the applicable abatement options for each segment of the natural gas system, followed by a more detailed discussion of the costs and benefits of selected abatement options. Engineering cost and benefit estimates represent equipment and operating costs in the United States for 1999. Whereas some abatement options are unique to a specific segment of the natural gas system, many are applicable in multiple segments.

Production Abatement Options

The production segment of the natural gas sector consists of wells, compressors, dehydrators, pneumatic devices, chemical injection pumps, heaters, meters, pipeline, and central gathering facilities. Abatement technologies associated with the production segment include

- catalytic converters for select well field engines and compressors,
- replacement of wet seals with dry seals in centrifugal compressors,
- direct/enhanced inspection and maintenance at production sites,
- flash tank separator installation in glycol dehydration systems,
- replacement of high-bleed pneumatic devices, and
- optimization of glycol recirculation rates.

One example of technology available to the production segment reduces glycol recirculation rates. Producers use triethylene glycol (TEG) in dehydrators to remove water from the natural gas coming out of the ground to meet pipeline quality standards. “Dry” TEG is combined with natural gas to remove moisture content before the natural gas is sold into a pipeline. The “rich” TEG then enters a boiler, where the foreign substances are evaporated and emitted into the atmosphere and the cycle repeats itself. The rate at which this process occurs is directly proportional to the amount of CH₄ emitted from glycol dehydrators. Production fields become less productive over time, but the rate at which the TEG recirculates is commonly based on the initial rate of production. As the well site matures, the TEG circulation rate becomes oversized. Recirculation can be recalculated to achieve sufficient moisture removal from the gas and minimize the release of CH₄ from the system. The following are the cost components for this abatement option:

- **Capital Costs.** This abatement option requires minimal or no additional equipment. However, similar to inspection and maintenance programs, the option is labor intensive, with the calculations and circulation adjustments conducted by engineering staff.
- **Annual Costs.** Annual costs primarily include the labor required to calculate new optimal recirculation rates each year as the well site becomes less productive.
- **Cost Savings/Benefits.** More CH₄ is brought to market for sale.

Processing Abatement Options

The processing segment consists of gas plant facilities that incorporate the use of vessels, dehydrators, compressors, acid gas removal (AGR) units, heaters, and pneumatic devices. Abatement technologies associated with the processing segment include

- fuel gas retrofit for reciprocating compressors,
- replacement of wet seals with dry seals in centrifugal compressors,
- conversion of gas pneumatic controls to instrument air, and
- DI&M at gas processing plants.

One example of abatement technology available to the processing segment converts gas pneumatic controls to compressed instrument air systems. Processing plants use pneumatic control systems to monitor various gas and liquid levels. As part of their normal operations, these devices release or bleed CH₄ into the atmosphere. Processing plants can substitute compressed air for natural gas within pneumatic systems. The following are the cost components for this abatement option:

- **Capital Costs.** Capital costs include the purchase and installation of a compressor, dehydrator, and volume tank—the major components of the instrument air system. Depending on the size of the gas processing plant, capital costs are estimated to be between \$4,500 and \$35,000 for the required capital equipment.
- **Annual Costs.** Annual costs include the annual energy, materials, and labor required to operate and monitor the equipment used in the compressed instrument air system. Annual energy costs are determined by the size of the compressor. Annual servicing costs range from \$800 to \$3,600 per year.
- **Cost Savings/Benefits.** By replacing natural gas with compressed instrument air, CH₄ is no longer being vented during normal operations. The benefit is the market value of CH₄ abated.

Transmission Abatement Options

The transmission segment of a natural gas system consists of transmission pipeline networks, compressor stations, and meter and pressure-regulating stations. The following are abatement technologies available to the transmission segment:

- conversion of gas pneumatic controls to instrument air,
- use of pipeline pumpdown techniques to lower gas line pressure before maintenance,
- DI&M at compressor stations and surface facilities,
- replacement of wet seals with dry seals in centrifugal compressors, and
- replacement of compressor rod packing systems.

One example of the abatement options available to the transmissions segment is DI&M at compressor stations. Compressor stations amplify pressure at several stages along a transmission natural gas pipeline to combat pressure loss over long distances. Over time, compressors and other related components become fatigued and may leak CH₄. The DI&M program reduces CH₄ emissions at compressor stations by identifying leaks and focusing maintenance on the largest leaks. The following are the cost components for this abatement option:

- **Capital Costs.** Capital costs include the cost of purchasing a leak detection device, which varies widely depending on the type of device used. The cost of screening devices ranges from \$1,000 to \$20,000. The cost of more sensitive sampling devices ranges from \$1,000 to \$10,000.
- **Annual Costs.** Annual costs include the cost of labor and materials to develop a maintenance schedule and implement the survey and maintenance annually. Annual costs account for the majority of costs associated with implementing this abatement option.
- **Cost Savings/Benefits.** Cost savings are approximately \$3 per thousand cubic feet (Mcf) of CH₄ recovered. The savings will depend on the intensity of the DI&M program and whether the leak, once detected, is fixed. The average station leak rate is approximately 41,000 Mcf per year, and the average annual cost savings is \$88,000 at a gas price of \$3 per Mcf (USEPA, 2003b).

Distribution Abatement Options

The distribution segment consists of main and service pipeline networks, meter and pressure-regulating stations, pneumatic devices, and customer meters. Abatement technologies available to the distribution segment include the

- use of hot taps in service pipeline connections,
- DI&M at gate stations,
- use of composite wrap for nonleaking pipeline defects, and
- use of a pipeline pumpdown technique to lower gas line pressure before maintenance.

An example abatement option available to the distribution segment is the use of a pipeline pumpdown technique when performing maintenance on segments of distribution pipeline. Operators routinely reduce line pressure and discharge gas from a pipeline during maintenance and repair activities. Using a pumpdown technique, which requires the use of inline and/or portable compressors to depressurize the section of pipeline, operators can mitigate CH₄ emissions. The following are the cost components for this abatement option:

- **Capital Costs.** Capital costs include the one-time costs of purchasing a portable compressor. The cost of this compressor varies by size and ranges from \$500,000 (300 psi) to \$3,000,000 (1,000 psi). Installation and freight costs are determined by the size of the compressor purchased.
- **Annual Costs.** Annual costs include fuel/energy, maintenance, and labor costs. Average energy costs vary based on the compressor's horsepower rating. Maintenance costs range from \$4 to \$9 per horsepower per month.
- **Cost Savings.** Cost savings will vary depending on the volume of gas available for recovery. The volume of gas available is determined by the length of pipeline to be repaired and the flow rate of gas during normal operations.

II.2.4 Results

This section presents the EMF-21 study's MAC results in tabular format.

II.2.4.1 Data Tables and Graphs

Table 2-10 presents the average breakeven price and the reduction in absolute and percentage terms for the mitigation options discussed in Section II.2.3.1.

The EMF regional baselines and MAC results of the EMF-21 study are presented in Tables 2-11 and 2-12 for 2010 and 2020 using a base energy price, a 10 percent discount rate, and a 40 percent tax rate. These MACs represent static percentage reductions in baselines for individual regions/countries and represent the official MACs used in climate change modeling. Figure 2-2 provides MACs for the five EMF countries/regions with the largest estimated emissions for natural gas systems in 2020.

The MACs presented in this section represent static abatement curves using breakeven prices built on the assumption of fixed mitigation cost and aggregate countrywide natural gas statistics. Appendix C to this chapter presents more recent efforts to develop an alternative framework for conducting MAC analysis that addresses the limitations of the EMF-21 MAC analysis.

Table 2-10: Natural Gas MACs for Countries Included in the Analysis

Technology	Breakeven Cost (\$/tCO₂eq)	Emissions Reduction (%) from baseline)	Emissions Reduction in 2010 (MtCO₂eq)	Emissions Reduction in 2020 (MtCO₂eq)
Assuming a 10% discount rate and a 40% tax rate				
P&T—use gas turbines instead of reciprocating engines	\$113.36	4%	0.21	0.27
P&T—compressors altering start-up procedure during maintenance	–\$15.22	0%	0.01	0.01
Prod-D I&M (chemical inspection pumps)	\$121.98	0%	0.01	0.01
Prod-D I&M (enhanced)	\$836.05	0%	0.01	0.01
Prod-D I&M (offshore)	\$49.51	0%	0.01	0.01
Prod-D I&M (onshore)	\$682.60	0%	0.01	0.01
Prod-D I&M (pipeline leaks)	\$55.82	1%	0.07	0.09
Installation of electric starters on compressors (production)	\$9,829.72	0%	0.00	0.00
Installation of flash tank separators (production)	\$85.47	2%	0.09	0.10
Installation of plunger lift systems in gas wells	\$3,233.11	0%	0.00	0.00
Portable evacuation compressor for pipeline venting (production)	\$178.89	0%	0.00	0.00
Reducing the glycol circulation rates in dehydrators (production)	–\$25.03	0%	0.01	0.02
Replace high-bleed pneumatic devices with compressed air systems (production)	\$85.36	5%	0.23	0.27
Replace high-bleed pneumatic devices with low-bleed pneumatic devices (production)	–\$12.22	4%	0.20	0.23
Surge vessels for station/well venting (production)	\$8,774.06	0%	0.00	0.00
Dry seals on centrifugal compressors (P&T)	\$36.75	3%	0.16	0.20
Fuel gas retrofit for blowdown valve	–\$26.67	2%	0.08	0.10
Reducing the glycol circulation rates in dehydrators (P&T)	–\$27.55	0%	0.01	0.01
Catalytic converter (P&T)	\$76.81	3%	0.16	0.20
P&T-D I&M (compressor stations)	–\$25.24	0%	0.02	0.03
P&T-D I&M (compressor stations: enhanced)	–\$24.45	0%	0.02	0.03
P&T-D I&M (enhanced: storage wells)	\$100.27	0%	0.00	0.00
P&T-D I&M (pipeline: transmission)	\$2,863.14	0%	0.00	0.00
P&T-D I&M (wells: storage)	\$79.74	0%	0.00	0.00
Installation of flash tank separators (P&T)	\$7.57	0%	0.01	0.01
Portable evacuation compressor for pipeline venting (P&T)	\$178.89	2%	0.10	0.13
Static-pacs on reciprocating compressors (P&T)	\$34.30	0%	0.01	0.02

(continued)

Table 2-10: Natural Gas MACs for Countries Included in the Analysis (continued)

Technology	Breakeven Cost (\$/tCO₂eq)	Emissions Reduction (%) from baseline)	Emissions Reduction in 2010 (MtCO₂eq)	Emissions Reduction in 2020 (MtCO₂eq)
Replace high-bleed pneumatic devices with compressed air systems (P&T)	\$88.69	2%	0.09	0.11
Replace high-bleed pneumatic devices with low-bleed pneumatic devices (P&T)	−\$12.22	2%	0.08	0.10
Surge vessels for station/well venting (P&T)	\$8,774.06	1%	0.08	0.09
D-D I&M (distribution)	−\$23.20	2%	0.12	0.15
D-D I&M (enhanced: distribution)	\$21.02	4%	0.22	0.27
Electronic monitoring at large surface facilities (D)	\$0.76	5%	0.27	0.33
Replacement of cast iron/unprotected steel pipeline (D)	\$19,347.78	7%	0.34	0.42
Replacement of unprotected steel services (D)	\$461,544.32	3%	0.14	0.17

Source: USEPA, 2003a. Adapted from Natural Gas Sector technology tables in Appendix B.

D = Distribution; I&M = Inspection and maintenance; P = Production; T = Transmission.

Table 2-11: Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	65.7	95.7	144.5
Annex I	517.3	556.9	639.2
Australia/New Zealand	6.1	9.6	15.2
Brazil	1.8	6.9	14.9
China	1.9	5.8	13.2
Eastern Europe	8.5	12.2	17.7
EU-15	25.2	25.4	26.4
India	15.8	35.7	61.4
Japan	0.4	0.4	0.4
Mexico	37.4	64.0	111.4
Non-OECD Annex I	255.9	277.0	299.6
OECD	301.9	349.8	459.4
Russian Federation	165.3	178.6	193.1
South & SE Asia	71.7	85.5	105.8
United States	145.7	138.6	164.8
World Total	972.4	1,271.5	1,695.8

Source: USEPA, 2006.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

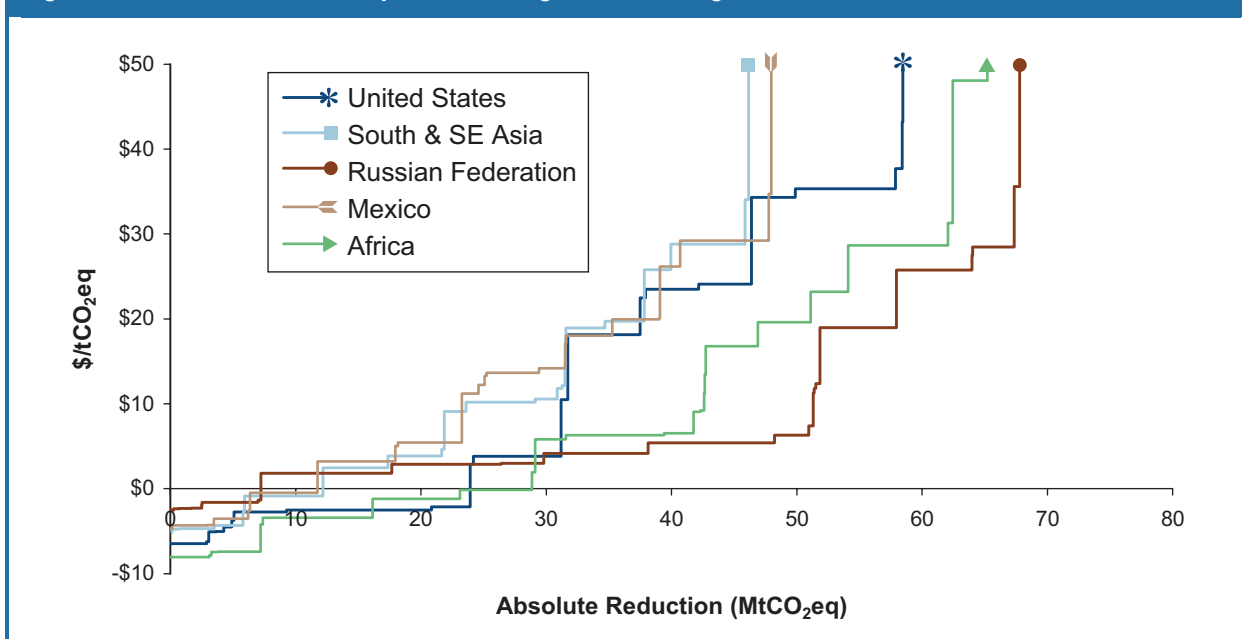
Note: World Total does not equal the sum of the countries listed in this table because the regional groupings are a subset of the full EMF regional grouping list. See Appendix A of this report for the full EMF list of countries by region.

Table 2-12: Natural Gas MACs for Countries Included in the Analysis

Country/Region	Percentage Reduction from Baseline (tCO ₂ eq)									
	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	20.38%	29.98%	37.85%	43.62%	56.03%	20.38%	29.98%	37.85%	43.62%	56.03%
Annex I	9.60%	24.21%	31.68%	35.12%	50.46%	8.98%	22.63%	29.62%	32.83%	47.18%
Australia/New Zealand	14.44%	20.06%	29.35%	36.94%	56.54%	14.44%	20.06%	29.35%	36.94%	56.54%
Brazil	16.64%	25.42%	36.87%	43.54%	57.79%	16.64%	25.42%	36.87%	43.54%	57.79%
China	17.05%	36.78%	43.33%	44.11%	45.92%	17.05%	36.78%	43.33%	44.11%	45.92%
Eastern Europe	19.05%	25.84%	34.03%	34.22%	48.71%	19.05%	25.84%	34.03%	34.22%	48.71%
EU-15	11.58%	18.38%	28.39%	29.01%	49.18%	11.58%	18.38%	28.39%	29.01%	49.18%
India	10.70%	28.15%	36.44%	43.49%	58.74%	10.70%	28.15%	36.44%	43.49%	58.74%
Japan	28.05%	28.12%	32.51%	46.17%	61.10%	28.05%	28.12%	32.51%	46.17%	61.10%
Mexico	11.06%	23.15%	37.02%	43.55%	57.62%	11.06%	23.15%	37.02%	43.55%	57.62%
Non-OECD Annex I	6.26%	27.29%	33.72%	35.50%	48.29%	6.09%	26.56%	32.81%	34.54%	46.99%
OECD	13.86%	20.73%	29.85%	35.60%	53.75%	12.14%	18.17%	26.16%	31.20%	47.11%
Russian Federation	3.75%	26.85%	33.14%	35.11%	48.42%	3.75%	26.85%	33.14%	35.11%	48.42%
South & SE Asia	11.51%	29.75%	37.75%	43.61%	56.22%	11.51%	29.75%	37.75%	43.61%	56.22%
United States	14.52%	19.24%	28.14%	35.47%	54.76%	14.52%	19.24%	28.14%	35.47%	54.76%
World Total	10.11%	24.98%	32.95%	37.90%	53.36%	10.19%	25.25%	33.24%	38.40%	53.81%

Source: USEPA, 2003a.

EU-15 = European Union.

Figure 2-2: EMF MACs for Top Five Emitting Countries/Regions from Natural Gas: 2020

Source: USEPA, 2003a.

Note: This table was constructed using percentage reductions from USEPA (2003), with baselines from USEPA (2005).

II.2.5 Summary

The methodology and data discussed in this section describe the MAC analysis conducted for the natural gas sector by the EMF-21 study. MACs for 2010 and 2020 were estimated based on aggregated industry data from each country or region. The MACs represent static estimates of potential CH₄ mitigation from natural gas systems based on available information regarding infrastructure and country-reported emissions estimates provided through the United Nation's Framework Convention on Climate Change emissions inventory reports.

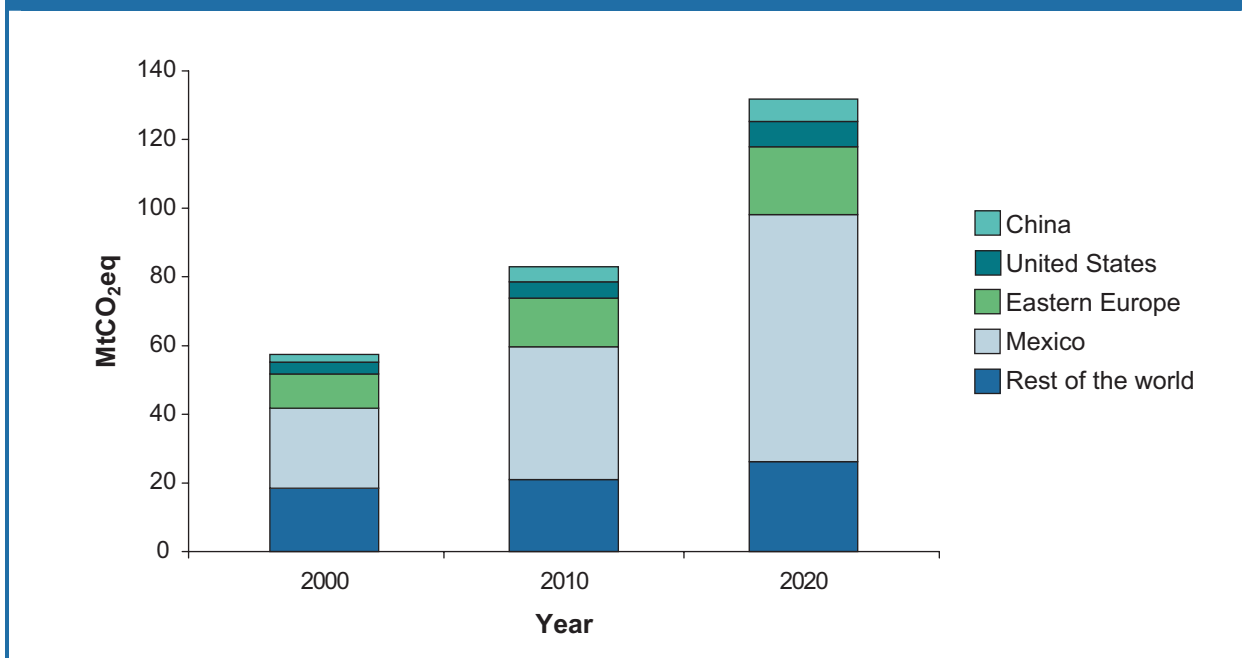
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II.3 Oil Sector

Worldwide CH₄ emissions from oil production accounted for more than 57 MtCO₂eq in 2000 (USEPA, 2006). Oil is the 11th largest source of anthropogenic CH₄ emissions globally. The USEPA estimates that oil production contributed approximately 0.5 percent of total global CH₄ emissions in 2000 (USEPA, 2006). Combined, Mexico, Eastern Europe, the United States, and China accounted for approximately 67 percent of the world's CH₄ emissions from oil (Figure 3-1). Global CH₄ emissions from oil are expected to grow by approximately 104 percent between 2005 and 2020.

Figure 3-1: CH₄ Emissions from Oil Production by Country: 2000–2020



Source: USEPA, 2006.

II.3.1 Introduction

Oil production begins by extracting crude oil either from underground production field wells (onshore) or platform oil derricks (offshore). The process of extracting oil involves drilling a deep well to access an oil reservoir underground. Once a well is drilled, compressors are used to pressurize the well, allowing the crude oil to exit the well through the vertical shaft. The compressed oil is transported via pipeline to a processing system and finally to a storage tank. Marine, rail, and truck tankers are the three major forms of transportation used by the oil sector to move crude oil from the site of production to the refinery. Pumping stations regulate the transfer of crude oil from storage tanks or pipelines onto transport tankers.

CH₄ emissions are associated with crude oil production, transportation, and refining operations. These oil production segments release CH₄ into the atmosphere as fugitive emissions, emissions from operational upsets, and emissions from fuel combustion (USEPA, 2004). In the United States, the largest emissions sources include high-bleed pneumatic devices, flaring, chemical injection pumps, and oil wellheads for light crude (USEPA, 2004). Emissions from oil production fields accounted for more than 97

percent of the total oil industry emissions. The remaining 3 percent was emitted from crude oil refinement (2 percent) and transportation (1 percent) (USEPA, 2004).

II.3.1.1 Emissions from Production Field Operations

During production field operations, CH₄ is released into the atmosphere via venting, accidental leaks, and fuel combustion. The USEPA suggests that the majority of emissions come from oil wellheads, storage tanks, and related field processing equipment such as compressors and chemical and injection pumps. CH₄ emissions from storage tanks, a dominant source of emissions, are created when the CH₄ entrained in crude oil under high pressure volatilizes as the oil enters the tank where it is stored at atmospheric pressure. Equipment leaks and vessel blowdowns during routine maintenance make up the second largest share of emissions from oil systems. The remaining emissions from field operations are associated with fugitive leaks and combustion through flares (USEPA, 2004).

Saudi Arabia and the United States were the two largest producers of oil in 2000, producing a reported 9.2 and 8.1 million barrels of crude oil per day, respectively. However, they do not have the largest CH₄ emissions from oil. Onshore production of oil generates less CH₄ emissions than offshore oil operations, because CH₄ produced onshore is more readily captured and transported for use. Oil production in many of the Organization of the Petroleum Exporting Countries (OPEC) members, including Saudi Arabia, consists primarily of onshore production operations. In contrast, a large share of the oil production in Mexico comes from offshore platforms.

II.3.1.2 Emissions from Crude Oil Transportation

Venting activities in transport tanks and marine vessel loading operations account for the majority of emissions in the transportation segment. Fugitive emissions from floating roof tanks account for the remainder of oil transportation emissions in the United States (USEPA, 2004).

II.3.1.3 Emissions from Crude Oil Refining

Most of the CH₄ entrained in crude oil has already escaped prior to the refining stage. Vented emissions that occur during normal operations account for the majority of emissions from this sector. Examples include refinery system blowdowns during routine maintenance and asphalt blowing. Fugitive leaks and combustion emissions are also a source of emissions. Most fugitive emissions come from leaks in a refinery's fuel gas system. Combustion emissions result from small amounts of unburned CH₄ in process heater stacks and from unburned CH₄ in engine exhausts and flares (USEPA, 2004).

II.3.1.4 Abatement Options

Three abatement options are discussed for the oil sector: flaring, direct use, and reinjection of gas into oil fields. The installation of a flaring system results in an estimated 98 percent reduction in fugitive emissions but can be costly in an offshore environment because of technical, environmental, and safety concerns. Direct use is applicable primarily to oil platforms, because CH₄ captured onshore is typically injected into the pipeline system (and is reflected in the baseline emissions). Reinjection of CH₄ back into the oil production field is an alternative to flaring or direct use and can enhance future oil recovery.

The following sections discuss the activity data and emissions factors used to develop baseline emissions, abatement options and their costs, and CH₄ MACs for oil production for selected countries. The chapter concludes with sensitivity analysis of key assumptions and a discussion of uncertainties and limitations.

II.3.2 Baseline Emissions Estimates

Baseline emissions from the oil sector are composed of emissions from production field operations, crude oil transportation, and crude oil refining. These emissions are classified either as fugitive emissions, vented emissions from operations, or emissions from fuel combustion (USEPA, 2004).

A country's baseline emissions estimate is the product of activity factors and emissions factors. The following section provides an overview of activity and emissions factors and concludes with a discussion of historical and projected baselines by type of equipment used.

II.3.2.1 Activity Factors

Activity factors characterize a given industry's size, either as the number of units (e.g., number of wells or miles of pipeline) or the flow through the units (million barrels [MMbbl] per day or year). The United States tracks 70 different activity factors for the oil industry. Some of these activity factors change annually in proportion to rates of crude oil production, transportation, and refinery runs, while others change in proportion to the number of facilities such as oil wells and petroleum refineries (USEPA, 2004). A detailed list of the activity factors related to production field operations, transportation, and refining is provided in Appendix D to this chapter (see Table D-1).

IPCC recognizes that this level of detailed information is not readily available in every country and therefore offers guidance on more aggregate activity factors that can be used to quantify the size of a country's oil system. Generally, aggregate activity factors such as production and consumption of oil are used.

Historical Activity Data

Oil production and consumption rates depend on economic conditions, global demand, and available reserves. For the purposes of this report, historical activity data were taken from publicly available reports, either from national communications or, when information was unavailable, from expert judgment (USEIA, 2005a). Table 3-1 reports oil production for selected countries in MMbbl per day for 1990 to 2003.

Projected Activity Data

Oil production is projected to increase by approximately 43 percent during the next 20 years. Table 3-2 and Table 3-3 list forecasted estimates for oil production and consumption between 2002 and 2025. In addition to OPEC countries continuing to expand production, Eastern European and some developing countries are forecasted to experience large proportional growth. Countries from the FSU in the Caspian Area are expected to experience the largest increase in production between 2002 and 2025, expanding from 1.66 to 6.22 MMbbl per day. Developing countries in regions such as Africa and the Middle East are also expected to expand production by 127 percent and 46 percent, respectively.

II.3.2.2 Emissions Factors and Related Assumptions

Emissions factors from oil production are defined as CH₄ emissions rates by either equipment type or operation. Equipment used in crude oil production includes wellheads, compressors, pipelines, storage tanks, and pneumatic devices. The United States has conducted a detailed bottom-up analysis to estimate average emissions factors by equipment or operation type. For countries or regions where this level of detail is unavailable, the IPCC's 1996 *Revised Guidelines Reference Manual* provides suggested approximate average emissions factors for each segment of oil systems for various regions around the world.

Table 3-1: Oil Production by Country: 1990–2003 (MMbbl per Day)

Country	1990	1995	2000	2002	2003
Saudi Arabia	7.0	9.2	9.5	8.8	10.1
United States	9.0	8.6	8.1	8.0	7.8
Russian Federation	N/A	6.2	6.7	7.7	8.5
Iran	3.1	3.7	3.8	3.5	3.8
Venezuela	2.3	3.0	3.4	2.9	2.6
Mexico	3.0	3.1	3.4	3.6	3.8
China	2.8	3.0	3.2	3.4	3.4
Norway	1.8	2.9	3.3	3.3	3.3
Canada	2.0	2.4	2.7	2.9	3.0
Iraq	2.1	0.6	2.6	2.0	1.3
United Arab Emirates	2.3	2.4	2.6	2.4	2.7
United Kingdom	1.9	2.8	2.5	2.5	2.3
Kuwait	1.2	2.2	2.2	2.0	2.3
Nigeria	1.8	2.0	2.2	2.1	2.2
Brazil	0.8	0.9	1.5	1.7	1.8
World Total	65.5	68.9	75.9	75.0	77.7

Source: USEIA, 2005a. Adapted from Table G-1 in the International Energy Annual 2003.

Historical Emissions Factors

Historical emissions factors have remained relatively constant. Countries use the IPCC's emissions factors cited in the 1996 *Revised Guidelines* to estimate annual emissions baselines each year from publication of the *Guidelines* to the present. Table 3-4 lists aggregate emissions factors provided by the IPCC for petroleum system production, transportation, and refinement. These emissions factors are based on top-down estimates of emissions by industry segment. However, as mentioned earlier, the detailed bottom-up approach taken by the United States may enable a more accurate estimate of baseline emissions by country. The U.S. oil industry emissions factors (see Tables D-1, D-2, and D-3) are also assumed to remain constant in the short term (USEPA, 2004).

IPCC and the United States report higher emissions factors in the production segment than in any other segment of a petroleum system (IPCC, 1996; USEPA, 2004). In the United States, pneumatic devices used in production field operations, flares, chemical injection pumps, and offshore platforms have the highest emissions factors of any type of equipment or operation in the petroleum system.

Projected Emissions Factors

Projected emissions factors from oil are expected to follow historical trends. IPCC and the USEPA predict only slight changes in their estimated emissions factors for the next 20 years.¹ Although new technology for equipment and operating procedures may improve in the future, current emissions factors for equipment and operations will increase slightly because of equipment age and usage.

¹ Emissions estimates do not necessarily reflect the IPCC emissions factors presented in Table 3-2.

Table 3-2: Forecasted Oil Production for Selected Countries (MMbbl per Day, Unless Otherwise Noted)

Production	2002	2010	2015	2020	2025
Conventional^a					
<i>Industrialized Countries</i>					
United States	9.3	9.9	9.7	9.5	9.3
Canada	2.1	1.8	1.7	1.6	1.6
Mexico	3.6	4.3	4.6	4.7	4.9
Western Europe ^b	6.9	6.4	6.0	5.6	5.0
Japan	0.2	0.1	0.1	0.1	0.1
Australia and New Zealand	0.8	1.0	0.9	0.9	0.9
Total industrialized	22.9	23.5	23	22.4	21.8
<i>Transitional Economies</i>					
FSU	11.2	13.6	15.3	16.4	17.5
Russian Federation	9.6	10.3	10.8	11.1	11.3
Caspian and other ^c	1.6	3.3	4.5	5.3	6.2
Eastern Europe ^d	0.2	0.3	0.4	0.4	0.5
Total transitional economies	11.4	13.9	15.7	16.8	18.0
<i>Emerging Economies</i>					
OPEC^e					
Asia	1.4	1.6	1.5	1.5	1.5
Middle East	19.0	25.8	27.9	32.1	36.7
North Africa	3.0	3.6	3.9	4.4	4.6
West Africa	2.0	2.5	2.7	3.1	3.6
South America	2.9	3.5	4.0	4.4	5.0
Non-OPEC					
China	3.0	3.7	3.6	3.6	3.5
Other Asia	2.4	2.7	2.8	2.8	2.7
Middle East ^f	1.9	2.3	2.5	2.6	2.8
Africa	2.9	3.8	4.9	5.5	6.5
South and Central America	3.8	4.6	5.5	6.0	6.5
Total emerging economies	42.3	54.1	59.3	66.0	73.4
Total Production (Conventional)	76.6	91.5	98.0	105.2	113.2
Total Production (Unconventional)^g	1.5	2.8	4.9	5.5	5.7
Total Production	78.1	94.3	102.9	110.7	118.9

Source: USEIA, 2005b. Adapted from the *International Energy Outlook 2004*. Table E4. World Oil Production by Region and Country, Reference Case, 1990–2025.

FSU = Former Soviet Union.

Note: Totals may not equal sum of components because of independent rounding. Data for 2002 and 2003 are model results and may differ slightly from official USEIA data reports.

^a Includes production of crude oil (including lease condensates), natural gas, plant liquids, other hydrogen and hydrocarbons for refinery feedstocks, alcohol and other sources, and refinery gains.

^b Includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Macedonia, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

^c Includes Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Krygyzstan, Latvia, Lithuania, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

^d Includes Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Serbia Montenegro, Slovakia, and Slovenia.

^e OPEC = Organization of Petroleum Exporting Countries. Includes Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela.

^f Non-OPEC Middle East includes Bahrain, Cyprus, Israel, Jordan, Lebanon, Oman, Syria, Turkey, and Yemen.

^g Includes liquids produced from energy crops, natural gas, coal, oil sands, and shale. Includes both OPEC and non-OPEC producers in the regional breakdown.

Table 3-3: Forecasted Oil Consumption for Selected Countries (MMbbl per Day, Unless Otherwise Noted)

Consumption	2002	2010	2015	2020	2025
<i>Mature Market Economies</i>					
United States	19.7	22.5	24.2	25.8	27.3
Canada	2.1	2.3	2.5	2.5	2.6
Mexico	2.0	2.3	2.5	2.8	3.0
Western Europe	13.8	14.1	14.3	14.4	14.9
Japan	5.3	5.3	5.4	5.4	5.3
Australia/New Zealand	1.0	1.2	1.3	1.4	1.5
Total mature market economies	43.9	47.7	50.1	52.2	54.6
<i>Transitional Economies</i>					
FSU	4.1	4.7	4.9	5.2	5.5
Eastern Europe	1.4	1.6	1.8	1.9	2.1
Total transitional economies	5.5	6.3	6.7	7.2	7.6
<i>Emerging Economies</i>					
China	5.2	9.2	10.7	12.3	14.2
India	2.2	3.1	3.7	4.2	4.9
South Korea	2.2	2.6	2.8	2.9	2.9
Other Asia	5.6	7.9	9.2	10.4	11.6
Middle East	5.7	7.3	8.0	8.6	9.2
Africa	2.7	3.7	4.3	4.6	4.9
South and Central America	5.2	6.8	7.8	8.5	9.3
Total emerging economies	28.7	40.6	46.3	51.6	57.0
Total Consumption	78.2	94.6	103.2	111.0	119.2

Source: USEIA, 2005b. Adapted from the *International Energy Outlook 2004*. Table A4. World Oil Consumption by Region, Reference Case, 1990–2025.

FSU = Former Soviet Union.

Note: Totals may not equal sum of components because of independent rounding. Data for 2002 and 2003 are model results and may differ slightly from official USEIA data reports.

Table 3-4: IPCC Emissions Factors for Petroleum Systems in Select Regions

Region	Petroleum System Industry Segments (kg/petajoule)				
	Production		Transportation	Storage	Refining
	Fugitive Emissions	Venting and Flaring			
Western Europe	300–5,000	1,000–3,000	745	90–1,400	20–250
United States and Canada ^a	300–5,000	3,000–14,000 ^a	745	90–1,400	20–250
FSU, Central and Eastern Europe	300–5,000	—	745	90–1,400	20–250
Other oil-exporting countries	300–5,000	—	745	90–1,400	20–250
Rest of the world	300–5,000	—	745	90–1,400	20–250

Source: IPCC, 1996. Adapted from Table 1-58 in 1996 Revised Guidelines Reference Manual.

FSU = Former Soviet Union.

^a In the United States and Canada, venting and flaring emissions are based on total production of both oil and gas produced.

II.3.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions from oil production.

Historical Emissions Estimates

Table 3-5 lists CH₄ emissions by country from 1990 through 2000. Historically, a country's emissions in the oil sector have correlated closely with oil production trends. Throughout the last decade, Mexico's oil emissions have grown to be the largest of any country. By 2000, Mexico had surpassed Romania, which experienced a sharp decline in baseline emissions over the same time period from 1990 through 2000.

Projected Emissions Estimates

As shown in Table 3-6, worldwide CH₄ emissions from oil are expected to increase by more than 80 percent from 2005 to 2020. Countries projected to experience increased production are also projected to have the largest growth in baseline emissions. Mexico and Brazil are projected to experience the largest increases at 160 percent and 157 percent, respectively, in their baseline emissions between 2005 and 2020.

II.3.3 The Cost of CH₄ Emissions Reductions from Oil

This section discusses opportunities for emissions reductions beyond existing baseline practices.

II.3.3.1 Abatement Option Opportunities

Three abatement options can be applied to the oil sector: flaring, direct use, and reinjection of gas into oil fields for enhanced oil recovery. Table 3-7 summarizes the costs and emissions reductions associated with each option.

Flaring in Place of Venting: Offshore and Onshore

The installation of a flaring system results in an estimated 98 percent reduction in fugitive emissions. Implementation of a flare in an offshore environment is more expensive because of technical, environmental, and safety concerns. For offshore application, total capital costs are estimated to be approximately \$818 per tCO₂eq, and O&M costs are estimated to be approximately \$25 per tCO₂eq. This abatement option has a technical lifetime of 15 years, yielding a breakeven price of approximately \$177 per tCO₂eq. For onshore sites, total capital costs are \$34 per tCO₂eq, and annual O&M costs are approximately \$1.10 per tCO₂eq, yielding a breakeven price of \$7 per tCO₂eq. Capital costs are assumed to be constant across countries, but O&M costs vary because of differences in labor costs across countries. This option has no monetary benefits because the CH₄ is combusted and vented as CO₂ to the atmosphere.

Direct Use of CH₄

This abatement option applies primarily to offshore platforms and has an estimated reduction efficiency of 90 percent. In this abatement option, CH₄ is used for consumption on oil platforms and/or converted to liquefied natural gas. A 15-year lifetime is estimated for this abatement option. Total capital costs for this abatement option are approximately \$55 per tCO₂eq. In the United States, O&M costs are estimated at \$1.10 per tCO₂eq (O&M cost varies by country). Benefits for this abatement option are the cost savings from substituting CH₄ for alternative energy sources. For the United States, the breakeven price for direct use of CH₄ is \$7 per tCO₂eq.

Table 3-5: Baseline Emissions from Oil Production, by Country: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
Mexico	18.8	19.3	23.3
Romania	20.1	11.4	8.3
China	1.2	1.4	2.2
United States	4.4	4.1	3.9
Nigeria	0.9	1.0	1.8
Iran	1.3	1.6	1.2
Kuwait	0.4	0.8	1.0
United Arab Emirates	1.1	1.2	1.2
Indonesia	1.2	1.0	1.9
Iraq	1.1	0.3	0.9
Ecuador	0.3	0.3	0.5
Canada	0.8	0.8	0.9
Bulgaria	0.6	0.7	0.6
Russian Federation	1.7	0.9	0.6
Lithuania	0.5	0.5	0.4
Rest of the world	8.2	8.2	8.7
World Total	62.6	53.5	57.4

Source: USEPA, 2006.

Table 3-6: Projected Baseline Emissions from Oil Production by Country: 2005–2020 (MtCO₂eq)

Country	2005	2010	2015	2020
Mexico	27.7	38.7	54.1	71.9
Romania	9.3	12.0	14.7	17.3
China	2.9	4.4	6.1	6.5
United States	3.4	3.7	4.1	4.5
Nigeria	2.2	2.7	3.3	4.1
Iran	1.8	2.2	2.7	3.6
Kuwait	1.0	1.3	1.4	1.8
United Arab Emirates	1.2	1.2	1.4	1.7
Indonesia	1.9	1.8	1.6	1.4
Iraq	0.8	0.9	1.0	1.3
Ecuador	0.6	0.6	0.8	1.1
Canada	0.9	0.9	1.0	1.0
Bulgaria	0.7	0.8	0.9	1.0
Russian Federation	0.7	0.8	0.9	1.0
Lithuania	0.6	0.6	0.7	0.8
Rest of the world	9.1	10.1	11.4	12.9
World Total	64.7	82.9	106.1	131.8

Source: USEPA, 2006.

Table 3-7: Cost of Reducing CH₄ Emissions from Oil

Abatement Technology	Year	Capital Cost (\$/tCO ₂ eq)	Annual Cost (\$/tCO ₂ eq)	U.S. Emissions Available for Reduction (MtCO ₂ eq) ^a	Reduction Efficiency	U.S. Emissions Reductions (MtCO ₂ eq)	Breakeven Price (\$/tCO ₂ eq) ^b
Flaring: offshore							
	2010	832.60	24.91	0.52	98%	0.51	\$170.35
	2020	832.60	24.91	0.53	98%	0.52	\$170.35
Flaring: onshore							
	2010	33.30	0.99	0.52	98%	0.51	\$6.82
	2020	33.30	0.99	0.53	98%	0.52	\$6.82
Direct use (offshore)							
	2010	55.51	1.11	0.52	90%	0.47	\$7.09
	2020	55.51	1.11	0.53	90%	0.48	\$7.09
Reinjection (onshore)							
	2010	66.61	2.21	0.52	95%	0.49	\$10.14
	2020	66.61	2.21	0.53	95%	0.50	\$10.14

^a Based on 50 percent of CH₄ emissions generated onshore and 50 percent offshore (USEPA, 2003).

^b Based on 15-year lifetime.

Reinjection of CH₄

Reinjection of CH₄ is an alternative to flaring or direct use. In this option, CH₄ captured from oil field operations is reinjected into the oil production field to enhance future oil recovery. Reinjection has an estimated reduction efficiency of 95 percent and a technical lifetime of 15 years. Total capital costs for this technology are approximately \$67 per tCO₂eq. Annual O&M costs are estimated to be \$2.20 per tCO₂eq in the United States, but vary by country. Benefits associated with this option include an additional increase in oil recovery and the mitigation of costs associated with flaring. The estimated breakeven price for the United States is \$10 per tCO₂eq.

II.3.4 Results

This section presents the EMF-21 study's MAC results in tabular format and provides a graph of the MACs for regions with the largest emissions.

II.3.4.1 Data Tables and Graphs

Percentages reported in Table 3-8 are from the report to the EMF provided by the USEPA (USEPA, 2003). It is estimated that there are no "no-regret" options for CH₄ abatement in the oil sector.

At a breakeven price of \$23 per tCO₂eq, the average percentage abatement is 17 percent for the United States and 38 percent for China, reflecting the high cost of offshore options. Technology changes have not been incorporated into abatement potential for CH₄ from the oil sector.

Table 3-8: Percentage Abatement for CH₄ for Selected Breakeven Price (\$/tCO₂eq): 2000

Technology	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (%) from Baseline)	Emissions Reduction in 2010 (MtCO ₂ eq)	Emissions Reduction in 2020 (MtCO ₂ eq)
Assuming a 10% discount rate and 40% tax rate				
Flaring instead of venting (offshore)	\$575.81	6%	0.02	0.03
Flaring instead of venting (onshore)	\$23.03	3%	0.01	0.01
Direct use	\$22.22	13%	0.05	0.06
Reinjection	\$31.22	8%	0.03	0.04

Source: USEPA, 2003. Adapted from Oil Sector technology tables in Appendix B to EMF report.

The EMF regional baselines and MAC results of the EMF-21 study are presented in Tables 3-9 and 3-10 for 2010 and 2020 using the base energy price, a 10 percent discount rate, and a 40 percent tax rate. These MACs represent static percentage reductions in baselines for individual regions/countries and represent the official MACs used in climate change modeling. Figure 3-2 provides MACs for the five EMF countries/regions with the largest estimated emissions from the oil sector in 2020.

Table 3-9: Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	3.4	4.7	7.4
Annex I	17.6	21.9	28.8
Australia/New Zealand	0.1	0.2	0.3
Brazil	0.3	0.3	0.5
China	2.2	4.4	6.5
Eastern Europe	10.0	14.1	19.7
EU-15	1.0	1.0	1.1
India	0.2	0.3	0.4
Japan	0.0	0.0	0.0
Mexico	23.3	38.7	71.9
Non-OECD Annex I	10.9	15.3	21.1
OECD	30.1	45.5	79.8
Russian Federation	0.6	0.8	1.0
South & SE Asia	2.5	2.5	2.3
United States	3.9	3.7	4.5
World Total	57.4	82.9	131.8

Source: USEPA, 2006.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

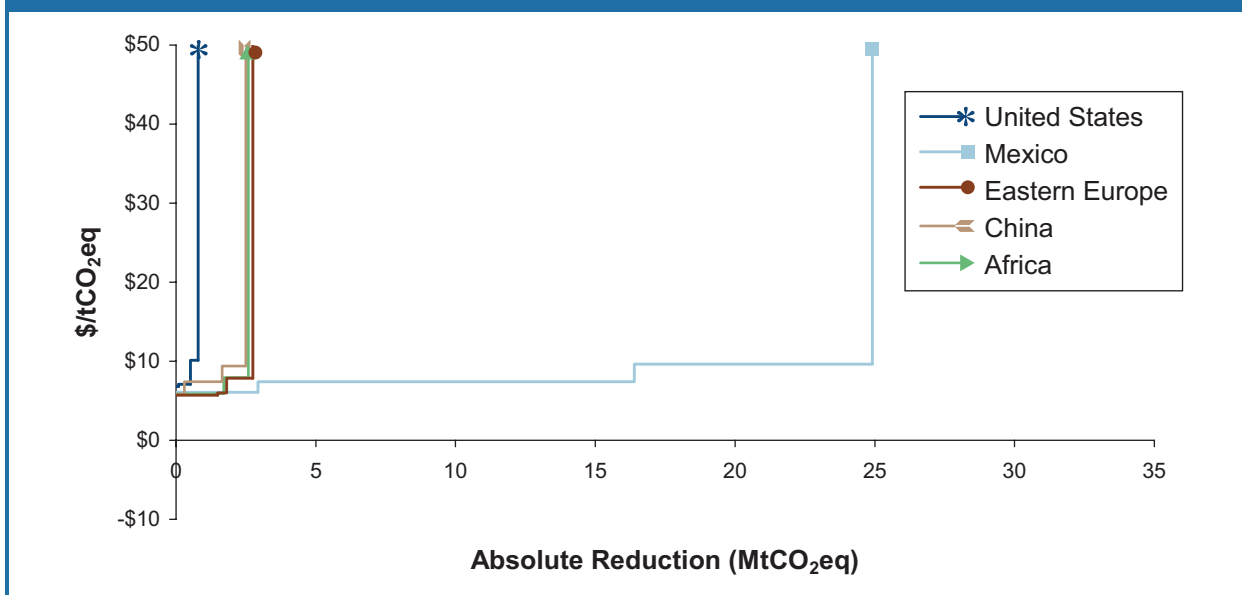
Note: World Total does not equal the sum of the countries listed in this table because the regional groupings are a subset of the full EMF regional grouping list. See Appendix A of this report for the full EMF list of countries by region.

Table 3-10: Oil System MACs for Countries Included in the Analysis

Country/Region	Percentage Reduction from Baseline (tCO ₂ eq)									
	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	0.00%	37.27%	37.27%	37.27%	46.05%	0.00%	37.27%	37.27%	37.27%	46.05%
Annex I	0.00%	21.48%	21.48%	21.48%	26.54%	0.00%	20.16%	20.16%	20.16%	24.91%
Australia/New Zealand	0.00%	22.07%	22.07%	22.07%	27.26%	0.00%	22.07%	22.07%	22.07%	27.26%
Brazil	0.00%	26.69%	26.69%	26.69%	32.97%	0.00%	26.69%	26.69%	26.69%	32.97%
China	0.00%	38.17%	38.17%	38.17%	47.15%	0.00%	38.17%	38.17%	38.17%	47.15%
Eastern Europe	0.00%	13.12%	13.12%	13.12%	16.20%	0.00%	13.12%	13.12%	13.12%	16.20%
EU-15	0.00%	11.71%	11.71%	11.71%	14.47%	0.00%	11.71%	11.71%	11.71%	14.47%
India	0.00%	17.54%	17.54%	17.54%	21.66%	0.00%	17.54%	17.54%	17.54%	21.66%
Japan	0.12%	0.22%	0.22%	0.22%	0.27%	0.12%	0.22%	0.22%	0.22%	0.27%
Mexico	0.00%	34.64%	34.64%	34.64%	42.79%	0.00%	34.64%	34.64%	34.64%	42.79%
Non-OECD Annex I	0.00%	31.67%	31.67%	31.67%	39.12%	0.00%	30.81%	30.81%	30.81%	38.06%
OECD	0.00%	24.55%	24.55%	24.55%	30.33%	0.00%	22.75%	22.75%	22.75%	28.11%
Russian Federation	0.00%	33.98%	33.98%	33.98%	41.97%	0.00%	33.98%	33.98%	33.98%	41.97%
South & SE Asia	0.00%	24.07%	24.07%	24.07%	29.73%	0.00%	24.07%	24.07%	24.07%	29.73%
United States	0.00%	17.67%	17.67%	17.67%	21.83%	0.00%	17.67%	17.67%	17.67%	21.83%
World Total	0.00%	28.08%	28.08%	28.08%	34.69%	0.00%	28.96%	28.96%	28.96%	35.78%

Source: USEPA, 2003.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 3-2: EMF MACs for Top Five Emitting Countries/Regions from Oil: 2020

Source: USEPA, 2003.

Note: Regional MACs were constructed using percentage reductions from USEPA (2003), with baselines from USEPA (2005).

II.3.5 Uncertainties and Limitations

Uncertainties and limitations persist despite attempts to incorporate all publicly available international oil sector information. Limited information on the oil systems of developing countries increases this uncertainty. Additional information would improve the accuracy of baseline emissions projections:

- **Improved Cost Data.** Improved documentation of oil CH₄ abatement options and their cost components would make it easier to estimate baseline reductions, given some estimate of market penetration.
- **Improved Emissions Factor Data.** Improved documentation of emissions factors for oil systems of countries outside the United States would enhance the accuracy of international analysis of CH₄ emissions.
- **Improved Abatement Option Data.** Improved abatement option data are needed to identify true abatement opportunities for oil systems. For example, although flares have long been thought of as a potential abatement option, new research suggests that some amount of CH₄ may be escaping combustion at the site of the flare. Accurate information on emissions factors is necessary before reduction efficiencies can be estimated.

II.3.6 Summary

The data discussed in this chapter demonstrate that oil is a significant source of greenhouse gas emissions, but because of information limitations for some countries, a more thorough cost analysis is not possible. Self-regulation by industry and changes in market structure may lead to reductions in emissions baselines in the future. However, to truly understand the potential benefits of an abatement option in an oil system and to estimate potential market penetration across countries, more information is needed.

II.3.7 References

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Section II: Energy Sector Appendixes

Appendixes for this section are available for download from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

III. Waste

Section III presents international emissions baselines and marginal abatement curves (MACs) for waste sources. There are two chapters, one addressing individual sources from the landfill sector and one addressing sources from the wastewater sector. These sources include emissions of methane (CH_4) and nitrous oxide (N_2O). MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can be downloaded in spreadsheet format from the USEPA's Web site at <<http://www.epa.gov/nonco2/econ-inv/international.html>>.

Section III—Waste chapters are organized as follows:

Methane (CH_4)

III.1 Landfill Sector

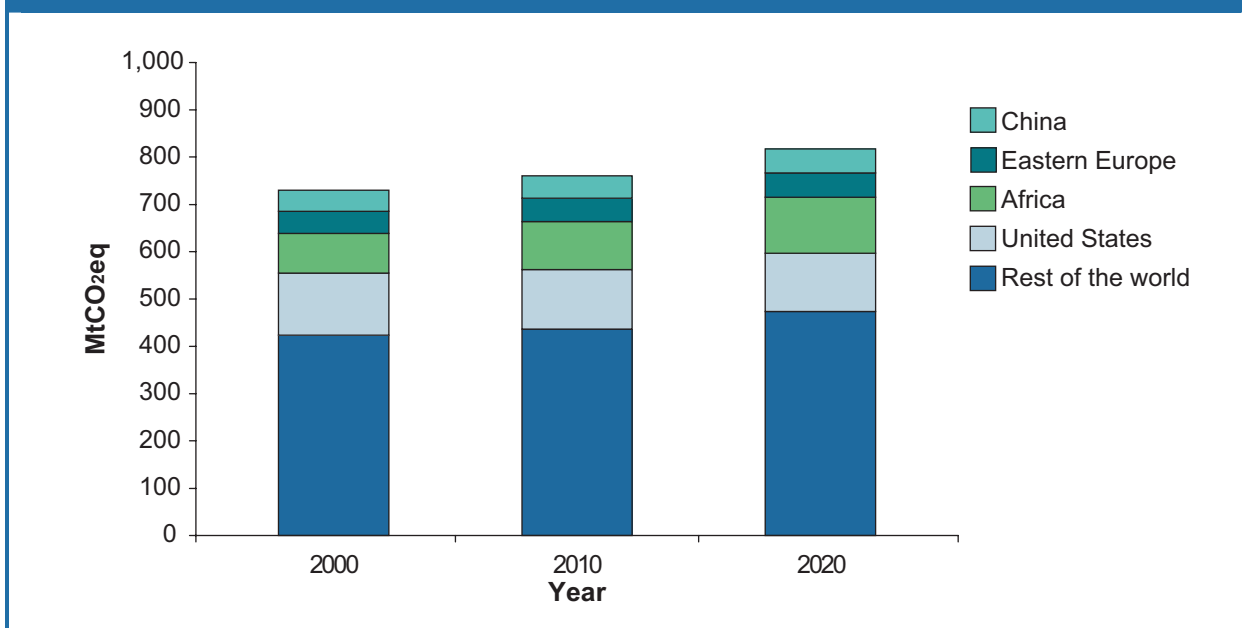
Methane (CH_4) and Nitrous Oxide (N_2O)

III.2 Wastewater Sector

III.1 Landfill Sector

Worldwide methane (CH_4) from the landfilling of municipal solid waste (MSW) accounted for over 730 million metric tons of carbon dioxide (MtCO_2eq) equivalent in 2000 and represented over 12 percent of total global CH_4 emissions. The United States, Africa, Eastern Europe, and China combined account for 42 percent of the world's CH_4 emissions from landfills (see Figure 1-1). Global CH_4 emissions from landfills are expected to grow by 9 percent between 2005 and 2020. Most developed countries have regulations that will constrain and potentially reduce future growth in CH_4 emissions from landfills. However, areas of the world such as Eastern Europe and China are projected to experience steady growth in landfill CH_4 emissions because of improved waste management practices diverting more MSW into managed landfills.

Figure 1-1: CH_4 Emissions from Municipal Solid Waste by Country: 2000–2020



Source: Environmental Protection Agency (USEPA), 2006.

III.1.1 Introduction

CH_4 from landfills is produced in combination with other landfill gases (LFGs) through the natural process of bacterial decomposition of organic waste under anaerobic conditions. The CH_4 along with other LFGs is generated over a period of several decades (usually beginning 1 to 2 years after the waste is put in place). CH_4 makes up approximately 50 percent of LFG, with the remaining 50 percent being CO_2 mixed with small quantities of other gases. If landfill CH_4 is not collected, it will escape to the atmosphere.

The production of landfill CH_4 gas depends on several key characteristics, including waste composition, landfill design, and operating practices, as well as local climate conditions. Two factors that will accelerate the rate of CH_4 generation within a landfill are an increased share of organic waste (paper, food scraps, brush) in the mix of MSW being landfilled and increased levels of moisture in the waste. In addition, if the landfill has used a soil cover (daily cover, intermediate cover, or final cover) in its

operations, a portion of the CH₄ will be oxidized as it passes through these soil layers and converted to CO₂. Many landfill management practices are regulated to control for health and environmental concerns.

The U.S. federal government currently requires all landfills to monitor and control landfill gas migration and requires larger landfills to collect and combust landfill gas to destroy the non-CH₄ organic compounds. Landfills with a design capacity greater than 2.5 million megagrams (or 2.8 million short tons) are subject to the New Source Performance Standards and Guidelines (NSPS/EG) of the Clean Air Act (USEPA, 1999a), referred to in this chapter as the “Landfill Rule.” Similar regulations exist in the European Union (EU-15) and other developed countries to control the CH₄ emissions from large landfills. However, in most developing countries, there are no regulations covering landfill CH₄ emissions. Despite efforts to control large landfill emissions, the landfill sector remains a significant source of CH₄ emissions.

Abatement options include the capture of CH₄ for flaring or energy production and enhanced waste management practices to reduce waste disposal at landfills (such as recycling-and-reuse programs). CH₄ recovery for energy use is another approach and is the focus of this report’s marginal abatement curve (MAC) analysis. Because of its low cost, flaring is the most commonly adopted abatement option; however, this report also considers two energy recovery options as viable alternatives to flaring that may provide greater financial incentive to landfill managers.

The following sections discuss the activity data and emissions factors used to develop baseline emissions, abatement options and their costs, and CH₄ MACs for the landfill sector. The chapter concludes with a discussion of uncertainties and limitations. As an appendix to this analysis, we discuss recent efforts to improve on the MAC methodology by incorporating technology change and by building the MACs from a population of individual landfills.

III.1.2 Baseline Emissions Estimates

This section discusses the characteristics of landfills and how the characteristics affect CH₄ emissions. In this section, we also describe historical and projected trends that influence baseline emissions from MSW landfills. In general, the quantity of CH₄ generated is determined by four main factors:

- population
- quantity of waste disposed of per capita
- composition of waste disposed of
- type of waste disposal site (landfill versus open dump)

It is commonly accepted that waste generation grows approximately proportional to a country’s population. In addition, countries with higher gross domestic product (GDP) per capita typically generate more waste per capita. The amount of waste generated per capita multiplied by the population determines the amount of MSW available for disposal.

The composition of waste, which influences CH₄ emissions rates, varies across countries. The level of recycling or reuse of plastics, metals, organics, and other inorganic waste affects both the amount of waste disposed of and the type of waste available to generate CH₄. Generally, formal recycling-and-reuse programs are incremental improvements employed by countries that already have sanitary landfills in place. However, open dumps often have high levels of recovery of both organic and inorganic materials from informal programs involving human activities and animal scavenging.

The type of waste disposal site also significantly influences CH₄ generation. There are generally three types of waste disposal sites—open dumps, controlled or managed dumps, and sanitary landfills. Open dumps are characterized by open fills with loosely compacted waste layers. Managed dumps are similar

to open dumps but are better organized and may have some level of controls in place. Open and controlled dumps are not conducive to CH₄ generation primarily because of aerobic conditions as well as other factors such as shallow layers and unconsolidated disposal (i.e., waste disposed in different parts of the same landfill site on different days). Sanitary landfills are sites designed and operated to accept MSW and employ waste management practices, such as mechanical waste compacting and the use of liners, daily cover, and a final cap (Intergovernmental Panel on Climate Change [IPCC], 1996). Developed countries primarily employ sanitary landfills. In developing countries, there is a mix of open dumps (in rural and some urban sites), managed dumps (mainly in larger townships), and sanitary landfills (in large cities).

III.1.2.1 Activity Data

This section discusses the historical and projected activity factors that determine CH₄ generation at solid waste disposal sites and policies set to improve waste management practices.

Historic Activity Data

Industrialized countries traditionally have the highest per capita waste generation rates and have accounted for the dominant share of global MSW production each year. Industrialized countries have also been the first to adopt sanitary landfills, employing waste compaction, dirt covers, and final caps. Sanitary landfills enable more waste to decay in an anaerobic environment, which ultimately leads to an increase in CH₄ production. However, industrialized countries have also led the way in adopting landfill gas (LFG) regulations and LFG utilization projects.

Developing countries historically have high population growth rates but use open dumps for waste disposal because of decentralized waste management programs and cost factors. Open dump waste disposal sites often do not provide the anaerobic conditions necessary to produce large quantities of CH₄. Some developing countries may have managed dumps that could create the anaerobic conditions required to generate CH₄ emissions. When calculating a country's baseline emissions, it is important to determine whether the country has any managed dumps. Additionally, economic growth in developing countries may result in an increased migration from rural communities to larger urban settings. Larger amounts of waste landfilled in the sanitary and managed dumps in these larger urban cities may potentially increase the amount of CH₄ generated.

Projected Activity Data

Globally, projections indicate that the amount of MSW being deposited into sanitary landfills is expected to grow. Developing countries are expected to move away from open dumps toward more sanitary landfills. The fraction of waste disposed of in landfills versus open dumps is expected to increase at the rate of per capita GDP growth.

Industrialized countries are expected to increase the level of LFG regulation and LFG utilization projects. These countries will also continue to improve or implement composting, recycling, and reuse programs. For example, in the United States the fraction of waste generated that is landfilled has decreased from 72 percent of all waste generated in 1989 to 56 percent of all waste generated in 2000 (USEPA, 2003b).

III.1.2.2 Emissions Factors and Related Assumptions

The emissions factors for sanitary landfills are defined as the CH₄ generated per ton of waste accumulated and are primarily determined by, but are not limited to, four factors: the type and age of the waste buried in the landfill, the quantity and types of organic compounds in the waste, the moisture

content of the waste, and temperature of the waste. Temperature and moisture levels are influenced by the surrounding climate. CH₄ emissions factors are significantly higher for sanitary landfills compared with open dumps because of the presence of anaerobic conditions.

Historical Emissions Factors

Industrialized countries have only recently begun adopting waste management practices such as recycle-and-reuse programs for organic materials. Before these programs were instituted, industrialized MSW had a higher organic material composition, which resulted in higher emissions factors.

Developing countries' emissions factors for landfills have historically been lower than industrialized countries because of the use of open dumps, which have shallow layers of rapidly decaying organic matter under aerobic conditions, preventing the accumulation of CH₄. In addition, open dumps make it easy for both animal scavengers and human waste pickers to remove food and paper, effectively reducing the amount of organic waste that would otherwise decay and ultimately generate CH₄. Fires are also common at open dump sites and can alter the composition of the MSW, reducing its ability to generate CH₄.

Projected Emissions Factors

Industrialized countries' emissions factors for landfills are projected to decrease. As these countries continue improving their waste management practices, more of the organic waste will be taken out of the MSW disposed of at landfills, thereby lowering the landfill's CH₄ generation potential. One example is the EU Landfill Directive, which has limited the amount of organic matter that can enter MSW facilities. Additionally, steady economic growth and small or negative population growth may again lower emissions factors for landfills in industrialized countries.

Emissions factors for developing countries' landfills will increase as these countries move away from open dumps toward sanitary landfills. Sanitary landfills typically do not allow for scavengers to reduce the organic composition of the MSW. This possibility, in combination with the lack of established recycling programs, could lead to a dramatic increase in the emissions factors for these landfills.

III.1.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline landfill emissions for both industrialized and developing countries. Figure 1-2 summarizes the components of landfill baseline CH₄ emissions, where incremental landfill management improvements, such as increased recycling programs, are accounted for through a reduction in the amount of waste accumulating at a landfill. This has a direct effect on the quantity of CH₄ generated at MSW landfills. In countries for which no emissions estimate was available, the IPCC Tier 1 methodology was used to estimate baselines using IPCC default values. For more detailed discussion of baseline emissions calculation methodology, see the USEPA's (2006) *Global Emissions Inventory Report*.

Historical Emissions Estimates

Table 1-1 lists the historical baselines for the world's leading countries in CH₄ emissions from landfills. The United States, by far the largest emitter of CH₄ from landfills, experienced a decline in baseline emissions as a result of the Landfill Rule and LFG utilization. Former Soviet countries of Eastern Europe, such as the Ukraine and Poland, have experienced gradual increases as these newly independent states begin to develop their waste management programs and a larger fraction of the MSW generated is disposed of at managed landfills.

Figure 1-2: Components of CH₄ Emissions from Landfills

$$\begin{aligned}
 &\text{Total landfill CH}_4 \text{ emissions} \\
 &\quad \text{equal} \\
 &\quad \text{CH}_4 \text{ generated from MSW landfills} \\
 &\quad \text{minus} \\
 &\quad \text{CH}_4 \text{ recovered and flared or used for energy} \\
 &\quad \text{minus} \\
 &\quad \text{CH}_4 \text{ oxidized from MSW landfills} \\
 &\quad \text{plus} \\
 &\quad \text{Methane emissions from industrial waste sites}
 \end{aligned}$$

Source: USEPA, 1999b.

Table 1-1: CH₄ Emissions from Municipal Solid Waste by Country: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
United States	172.2	162.4	130.7
China	40.4	42.6	44.6
Mexico	26.0	28.5	31.0
Canada	18.5	20.4	22.9
Russian Federation	37.8	37.8	35.1
Saudi Arabia	12.5	14.4	16.8
India	10.7	12.2	13.9
Brazil	13.0	14.5	15.6
Ukraine	14.2	14.5	12.1
Poland	16.1	15.9	17.0
South Africa	14.1	15.2	16.3
Turkey	8.2	8.9	9.7
Israel	6.6	7.8	8.8
Australia	7.5	8.3	8.0
Dem. Rep. of Congo (Kinshasa)	5.0	5.9	6.4
Rest of the world	358.7	360.4	341.6
World Total	761.4	769.7	730.3

Source: USEPA, 2006.

Historically, in developed countries, baseline CH₄ emissions from landfills are decreasing because of improved recovery technologies and mandated regulation to capture and control LFG (which includes CH₄) produced at the world's CH₄-producing landfills. Many countries have instituted regulations that require large landfills to install CH₄ capture-and-flaring systems either for safety or environmental concerns. For example, the United States enacted the Landfill Rule in 1996; the EU and the United Kingdom have enacted similar legislation to limit LFG generation or require its collection and control. The landfill rule requires landfill gas to be collected and combusted either through flaring or use at landfills that have a design capacity greater than 2.5 million metric tons (Mt) and 2.5 million cubic meters

(m³). This rule and similar rules in other developed countries have reduced the amount of CH₄ in the baseline estimates for each year after 1999.

Developing countries are increasing the fraction of waste disposed of at landfills as the amount of waste generated increases with per capita GDP. However, as discussed earlier, open dumps have been the primary method for waste disposal in developing countries, and because of the characteristics of these landfills, they tend not to produce large amounts of CH₄. Open dumps have kept CH₄ baseline emissions from landfills in developing countries low. However, very large open dumps and managed dumps can be significant sources of CH₄ emissions given sufficient conditions, such as depth, the amount of waste in place, and the rate of waste accumulation annually.

Projected Emissions Estimates

Worldwide CH₄ emissions from landfills are expected to decrease in industrialized countries and increase in developing countries. Industrialized countries' baselines will continue to decline because of expanding recycling-and-reuse programs, increased LFG regulation, and improved LFG recovery technologies. Developing countries' baseline landfill emissions are expected to increase because of their rapidly expanding populations—trending away from open dumps to sanitary landfills to improve health conditions—and because of a lack of formal recycling programs in the near future. Formal recycling programs typically follow the adoption of sanitary landfills. Table 1-2 lists the projected baseline emissions for the world's top emitters over the period from 2005 to 2020 in MtCO₂eq.

Table 1-2: Projected Baseline CH₄ Emissions from Municipal Solid Waste by Country: 2005–2020 (MtCO₂eq)

Country	2005	2010	2015	2020
United States	130.6	125.4	124.1	123.5
China	46.0	47.5	48.8	49.7
Mexico	33.3	35.5	37.4	39.2
Canada	25.3	27.7	30.7	33.6
Russian Federation	34.2	33.2	32.2	31.1
Saudi Arabia	19.4	22.1	24.8	27.5
India	15.9	17.1	18.1	19.1
Brazil	16.6	17.5	18.3	19.0
Ukraine	13.4	14.7	16.4	18.0
Poland	17.0	17.0	17.0	17.0
South Africa	16.8	16.6	16.4	16.2
Turkey	10.4	11.0	11.6	12.1
Israel	9.7	10.6	11.3	11.9
Australia	8.7	9.4	10.6	11.9
Dem. Rep. of Congo (Kinshasa)	7.4	8.6	9.8	11.2
Rest of the world	342.7	346.7	360.5	375.9
World Total	747.4	760.6	788.1	816.9

Source: USEPA, 2006.

Developing nations are projected to experience only slight declines in baseline emissions through government policies such as the Landfill Rule passed in the United States in 1996. As recovery techniques improve, the number of landfills that can profit from the LFG recovery will increase, which will continue to drive down the level of baseline emissions in developed as well as developing countries.

III.1.3 Cost of Emissions Reductions from Landfills

CH₄ emissions from landfills can be reduced using two approaches:

- capture the CH₄ and flare it or use it for energy and
- change waste management practices to reduce waste disposal at landfills by adding composting and recycling-and-reuse programs.

CH₄ recovery for flaring or energy is the most popular approach and is the focus of this report's cost analysis. However, documented or expected changes in disposal rates due to composting and recycling are accounted for in the baseline emissions estimates for each country.

III.1.3.1 Abatement Option Opportunities

Collection systems are present in most landfills as a mechanism to prevent migration of the gas to on-site structures or away from the landfill to adjacent property and to prevent the release of non-CH₄ organic compounds to the atmosphere. Following the collection of CH₄, the landfill operator must make a decision to flare, pump the gas to an end user for process heat, or generate electricity. Table 1-3 specifies the components of the gas collection and flaring system and direct-use system.

Table 1-3: Components of Collection and Flaring and LFG Utilization Abatement Options

System	Type of Equipment
Collection and flaring	Wells
	Wellheads and gathering pipeline system
	Knockout, blower, and flare
Utilization (i.e., electricity production and direct use)	Skid mounted filter
	Compressor
	Dehydrator unit
	Pipeline
	Turbine, engine, or boiler

Source: USEPA, 2003a.

The USEPA's LFG cost model estimates LFG generation, one-time capital costs, annual operation and maintenance (O&M) fees, and the quantity of gas recoverable for flaring or utilization for individual landfills. An expected technology lifetime of 15 years is used. This section discusses the one-time capital and annual costs and the annual cost savings for the two most popular options: collection and flaring and utilization. For a complete list of the technology options considered by the Economic Modeling Forum (EMF) 21 study for the landfill sector, see Table 1-4 below.

Collection and Flaring

The presence of CH₄ can be a public health concern, as well as a safety hazard at landfills if the concentration builds up. For this reason, large landfills have historically removed the CH₄ and then combusted the gas through flaring. Gas is collected through vertical wells and a series of horizontal

collectors typically installed following the closing of a landfill cell. Vertical wells are the most common type of well, while horizontal collectors are used primarily for deeper landfills and landfill cells that are actively being filled. Once captured, the gas is then channeled through a series of gathering lines to a main collection header. The USEPA recommends that the collection system be designed so that an operator can monitor and adjust the gas flow.

- **Capital Costs.** This abatement option requires the installation of vertical or horizontal wells; wellheads and gathering pipeline system; and a knockout, blower, and flare system. The USEPA's cost model estimates one well for every acre of landfill at a cost of \$7,200 per well. The gathering pipeline system's cost is determined by the number of wells at the landfill. The USEPA estimates the cost for the collection system as a fixed cost of \$19,000, plus a cost of \$8,756 per well. Finally, the cost of the knockout, blower, and flare system is determined by the gas flow rate. For example, if a landfill produced 1,000,000 cubic feet per day, the USEPA estimates the cost to be approximately \$200,000.
- **Annual Costs.** Annual costs include labor costs associated with monitoring the gas flows, moving or maintaining gas collection systems, and maintaining the flare. Additionally, there is an annual cost associated with the electricity used by blowers. Annual costs are typically 10 percent of one-time capital costs.
- **Cost Savings/Benefits.** Increased environmental and public health benefits, as well as increases in safety at the landfill site, are the primary benefits. The flaring system is an effective way of reducing large quantities of CH₄ emissions from landfills. Additional nonmarket benefits include the reduction of volatile organic compounds (VOCs) and reduced odor.

LFG Utilization Systems

Components of a capture and utilization abatement option for the landfill sector include a landfill gas collection system, utilization pumping system, or some mechanism such as a turbine for generating energy through the combustion of landfill CH₄ gas. LFG is extracted from landfills using a series of vertical or horizontal wells and a blower (or vacuum) system. This system directs the collected gas to a central point, where it can be processed and treated depending on the ultimate use of the gas. From this point, the gas simply can be flared or used to generate electricity, or the gas can be pumped to an end-user for process heat. Additional direct-use options, such as fuel to run leachate evaporators and liquid natural gas production, also reduce CH₄ emissions.

In addition, landfill CH₄ gas can be transported and used in industrial processes, such as boilers, drying operations, kiln operations, and cement and asphalt production. Gas collected from the landfill can be piped directly to local industries where it is used as a replacement or supplementary fuel. The ideal customers will have a steady, annual energy demand that will use a large percentage or all of the landfill's gas flow.

- **Capital Costs.** Utilization systems may require the installation of a skid-mounted filter, compressor, and dehydrator unit and mile(s) of pipeline to carry gas to the customer. Costs for the skid-mounted filter, compressor, and dehydrator unit are based on the gas flow rate. For a landfill with a gas flow rate of 1 million cubic feet per day, the USEPA estimates the installed costs of the filter, compressor, and dehydrator to be approximately \$180,000. The USEPA estimates the installation cost for the pipeline is \$264,000 per mile.
- **Annual Costs.** Annual costs are composed primarily of electricity usage by the compressor and dehydrator unit. Estimated annual costs for O&M and electricity are \$100,000.

- **Annual Savings/Benefits.** Annual benefits are determined by the quantity of gas sold, the British thermal unit (Btu) content of the landfill gas, and the current market price of natural gas. Given the 2004 price of natural gas in the United States, annual benefits can be up to 10 times as great as annual costs.

III.1.4 Results

This section presents the EMF-21 study's MAC results in tabular format.

III.1.4.1 Data Tables and Graphs

Table 1-4 presents the average breakeven price and the reduction in absolute and percentage terms for the mitigation options discussed in Section III.1.3.1. Table 1-5 presents the baseline emissions for landfills by EMF regional grouping. Table 1-6 presents the percentage reduction in the baseline emissions at specific breakeven prices, and Figure 1-3 provides MACs for the five EMF countries/regions with the largest estimated emissions from MSW landfills in 2020.

Table 1-4: Breakeven Prices of MSW Landfill Technology Options

Technology	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (%) from baseline)	Emissions Reduction in 2010 (MtCO ₂ eq)	Emissions Reduction in 2020 (MtCO ₂ eq)
Assuming a 10% discount rate and a 40% tax rate				
Anaerobic digestion 1 (AD1) ^a	\$36.03	10%	0.16	0.16
Anaerobic digestion 2 (AD2) ^b	\$428.74	10%	0.16	0.17
Composting (C1) ^c	\$243.45	13%	0.45	0.52
Composting (C2) ^d	\$265.41	12%	0.43	0.49
Mechanical biological treatment	\$362.94	10%	0.16	0.16
Heat production	-\$16.70	9%	0.31	0.36
Increased oxidation	\$265.20	6%	0.21	0.24
U.S. direct gas use (profitable at base price)	\$0.90	10%	0.34	0.39
Electricity generation	\$73.02	10%	0.34	0.39
Direct gas use (profitable above base price)	\$8.09	10%	0.34	0.39
Flaring	\$24.69	10%	0.34	0.39

Source: USEPA, 2003c. Adapted from landfill technology tables in Appendix B.

^a AD1 expedites the natural decomposition of organic material without oxygen by using a vessel that excludes oxygen and maintains the temperature, moisture content, and pH close to their optimum values. CH₄ can be used to produce heat and/or electricity.

^b AD2 expedites the natural decomposition of organic material without oxygen by using a vessel that excludes oxygen in the same way as AD1, but with additional income from compost.

^c C1 involves degradation of the organic matter under aerobic conditions. It requires separating organic matter from the waste stream. Finished compost has a market value because it is used to enhance soil in horticulture/landscape and agricultural sites.

^d C2 involves the degradation of organic matter under aerobic conditions and the separation of organic matter from the waste stream in the same way as C1, but there are larger costs.

Table 1-5: Baseline Emissions by EMF Regional Grouping: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	84.2	101.1	118.8
Annex I	349.6	315.7	312.4
Australia/New Zealand	9.4	11.0	13.6
Brazil	15.6	17.5	19.0
China	44.6	47.5	49.7
Eastern Europe	47.2	49.7	51.9
EU-15	84.6	46.3	32.7
India	13.9	17.1	19.1
Japan	3.9	3.1	2.4
Mexico	31.0	35.5	39.2
Non-OECD Annex I	62.2	65.1	69.1
OECD	328.6	297.0	293.5
Russian Federation	35.1	33.2	31.1
South & SE Asia	23.6	27.9	31.5
United States	130.7	125.4	123.5
World Total	730.3	760.6	816.9

Source: USEPA, 2006.

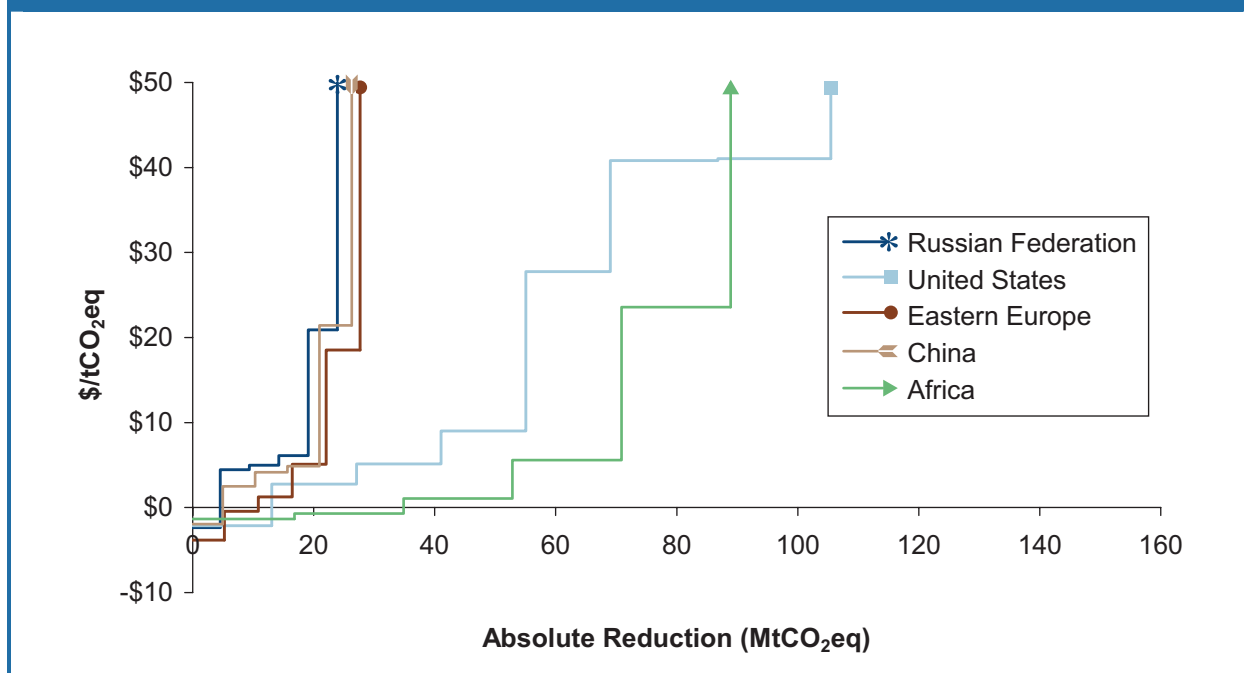
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-6: MSW Landfill MACs for Countries Included in the Analysis

Country/Region	Percentage Reduction from Baseline in tCO ₂ eq									
	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	20.71%	42.14%	52.86%	52.86%	87.31%	20.71%	42.14%	52.86%	52.86%	87.31%
Annex I	11.16%	38.89%	45.45%	63.58%	88.25%	11.54%	40.18%	46.96%	65.70%	91.19%
Australia/New Zealand	7.00%	29.50%	46.50%	46.50%	90.12%	7.00%	29.50%	46.50%	46.50%	90.12%
Brazil	20.71%	42.14%	52.86%	52.86%	87.31%	20.71%	42.14%	52.86%	52.86%	87.31%
China	10.00%	42.14%	52.86%	52.86%	87.31%	10.00%	42.14%	52.86%	52.86%	87.31%
Eastern Europe	20.71%	42.14%	52.86%	52.86%	87.31%	20.71%	42.14%	52.86%	52.86%	87.31%
EU-15	7.00%	29.50%	46.50%	46.50%	90.12%	7.00%	29.50%	46.50%	46.50%	90.12%
India	10.00%	52.86%	52.86%	52.86%	87.31%	10.00%	52.86%	52.86%	52.86%	87.31%
Japan	31.50%	66.00%	66.00%	66.00%	90.12%	31.50%	66.00%	66.00%	66.00%	90.12%
Mexico	10.00%	42.14%	52.86%	52.86%	87.31%	10.00%	42.14%	52.86%	52.86%	87.31%
Non-OECD Annex I	10.00%	42.14%	52.86%	52.86%	87.31%	9.20%	38.76%	48.61%	48.61%	80.30%
OECD	11.42%	38.42%	44.53%	64.55%	88.37%	11.91%	40.05%	46.43%	67.31%	92.14%
Russian Federation	10.00%	42.14%	52.86%	52.86%	87.31%	10.00%	42.14%	52.86%	52.86%	87.31%
South & SE Asia	10.00%	42.14%	52.86%	52.86%	87.31%	10.00%	42.14%	52.86%	52.86%	87.31%
United States	10.00%	42.14%	42.14%	80.71%	87.31%	10.00%	42.14%	42.14%	80.71%	87.31%
World Total	11.71%	40.54%	48.95%	58.35%	87.81%	11.82%	40.68%	49.62%	56.84%	87.76%

Source: USEPA, 2003c.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 1-3: EMF MACs for Top Five Emitting Countries/Regions from Landfills: 2020

The MACs presented in this section represent static abatement curves using breakeven prices built on the assumption of fixed mitigation cost, and aggregate countrywide landfill statistics. Appendix E presents more recent efforts to develop an alternative framework for conducting MAC analysis that addresses the limitations of the EMF-21 MAC analysis for the landfill sector.

III.1.4.2 Uncertainties and Limitations

Uncertainty and limitations persist despite attempts to incorporate all publicly available information on international landfill sectors. Additional information would improve the accuracy of the MACs' projections.

- **Landfill Populations.** A major source of uncertainty in the MACs is due to a lack of reliable information on the landfill population for all countries. Improved information on waste acceptance rates, waste composition, trends in waste management practices, and landfill capacity data by landfill for each country would greatly improve the analyst's ability to calculate benefits and hence breakeven prices.
- **Climate Change.** The presence of moisture plays a large role in determining the CH₄ generation rate for landfills in each country. Improved projected and historical data on the weather conditions at future and existing landfills would contribute to improving the accuracy of our estimations of CH₄ generation. This would also contribute to the heterogeneity of each country's MAC and of the landfills within each country.
- **Country-Specific Waste Management Practices.** Improved documentation of waste management practices would allow deviations from the normal assumption that waste generation increases along with population. Instituting recycling-and-reuse programs reduces the fraction of waste deposited in the landfills.

- **Adjusting Costs for Specific Domestic Situations.** Currently, the technologies considered in this report are available in the United States, Canada, and Western Europe for the costs reported. However, countries other than these countries may be faced with higher costs because of transportation and tariffs associated with purchasing the technology from abroad or could be faced with lower costs due to domestic production of these technologies. Data on domestically produced technologies, both costs and reduction efficiencies, are not available.
- **Country-Specific Tax and Discount Rates.** A single tax rate is applied to landfills and landfills in all countries to calculate the annual benefits of each technology. Tax rates can vary across countries and in the case of state-run mines and landfills in China, taxes may be less applicable. Similarly the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately calculate benefits and hence breakeven prices.

III.1.5 Summary and Analysis

The methodology and data discussed in this section describe the MAC analysis conducted for the landfill sector by the EMF-21 study. MACs for 2010 and 2020 were estimated based on aggregated industry data from each country or region. The MACs represent estimates of potential CH₄ mitigation from landfills based on available information regarding MSW practices, infrastructure, climate, and country reported emissions estimates provided through the United Nation's Framework Convention on Climate Change (FCCC) emissions inventory reports.

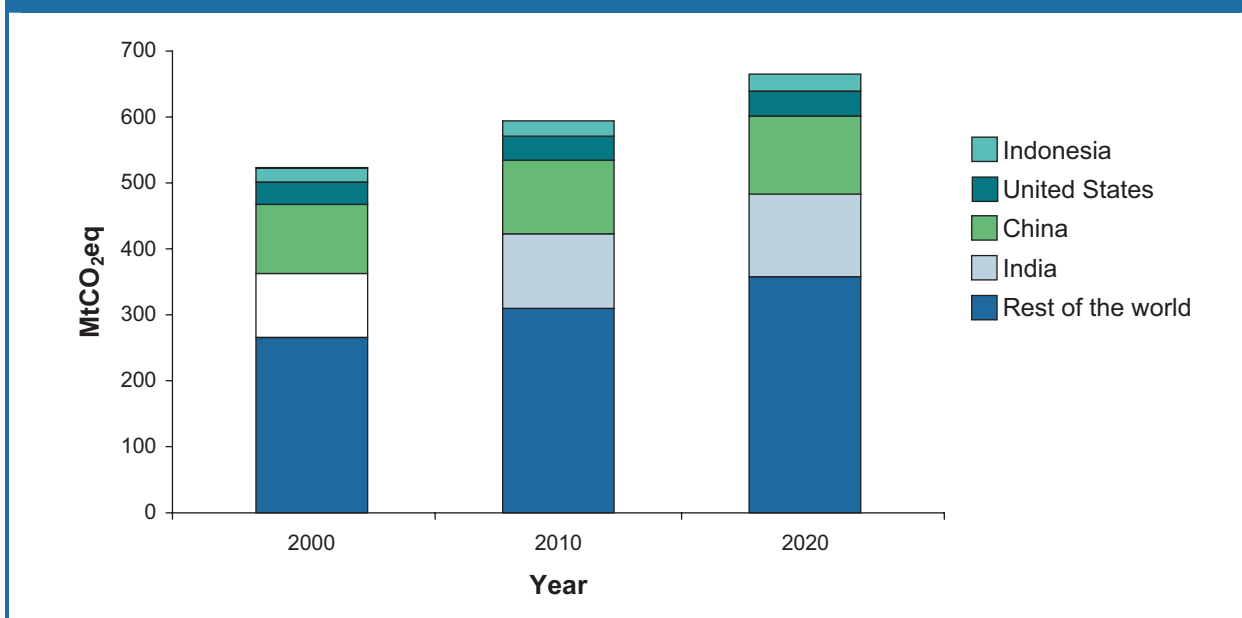
III.1.6 References

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III.2 Wastewater Sector

Worldwide CH_4 from wastewater accounted for more than 523 MtCO_2eq in 2000. Wastewater is the fifth largest source of anthropogenic CH_4 emissions, contributing approximately 9 percent of total global CH_4 emissions in 2000. India, China, the United States, and Indonesia combined account for 49 percent of the world's CH_4 emissions from wastewater (see Figure 2-1). Global CH_4 emissions from wastewater are expected to grow by approximately 20 percent between 2005 and 2020.

Figure 2-1: CH_4 Emissions from Wastewater by Country: 2000–2020

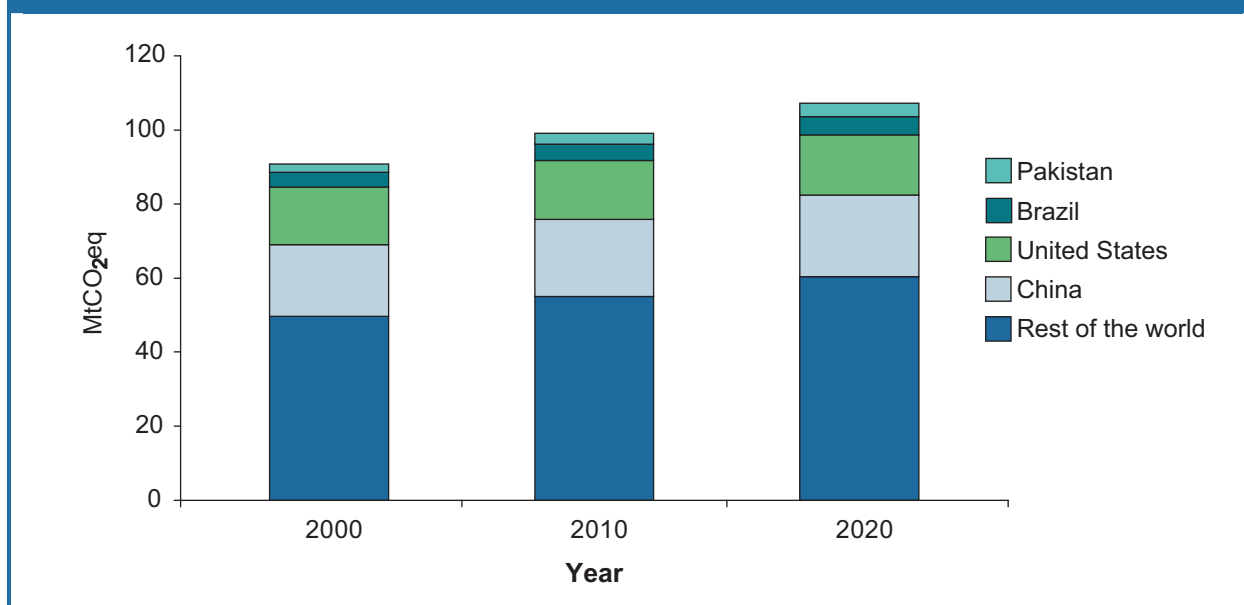


Source: USEPA, 2006.

Wastewater is also a significant source of nitrous oxide (N_2O). Worldwide, N_2O emissions from wastewater accounted for approximately 91 MtCO_2eq in 2000 (see explanatory note 1). Wastewater as a source is the sixth largest contributor to N_2O emissions, accounting for approximately 3 percent of N_2O emissions from all sources. Indonesia, the United States, India, and China accounted for approximately 50 percent of total N_2O emissions from domestic wastewater in 2000 (see Figure 2-2). Global N_2O emissions from wastewater are expected to grow by approximately 13 percent between 2005 and 2020. This chapter only discusses the mitigation options that may be available to control CH_4 at wastewater treatment plants. No formal MAC analysis is presented for this sector because data are insufficient on wastewater systems' infrastructure and abatement technology costs.

III.2.1 Introduction

Wastewater from domestic (sewage) and industrial sources is typically moved through a wastewater sewer system to a centralized wastewater management treatment center. At the treatment center, soluble organic material, suspended solids, pathogenic organisms, and chemical contaminants are removed from water using biological processes in which microorganisms consume the organic waste. This results in the production of biomass sludge. The microorganisms can perform this biodegradation process in aerobic and anaerobic environments, the former producing CO_2 and the latter producing CH_4 .

Figure 2-2: N₂O Emissions from Wastewater by Country: 2000–2020

Source: USEPA, 2006.

Wastewater treatment plants (WWTP) may be located on-site or off-site. In the case of domestic wastewater, septic tanks are an example of an on-site treatment plant for domestic wastewater, while a centralized municipal WWTP is an example of an off-site facility. The USEPA estimates that 25 percent of domestic wastewater is treated through on-site facilities such as septic tanks (USEPA, 2004). Centralized WWTP requires that the wastewater be transported to the facility through a municipal sewer system.

III.2.1.1 Emissions from Wastewater Systems

CH₄ is produced by decay of organic material in wastewater as it decomposes in anaerobic environments. CH₄ emissions from wastewater are determined by the amount of organic material produced and the extent to which this material is allowed to decompose under anaerobic conditions. The organic content of wastewater is typically expressed in terms of either biochemical oxygen demand (BOD) or chemical oxygen demand (COD) (IPCC, 1996a). Most developed countries use centralized aerobic wastewater treatment facilities with closed anaerobic sludge digester systems to process municipal and industrial wastewater. Employment of these practices increases CH₄ generation but ultimately reduces baseline emissions.

N₂O is produced during both the nitrification and denitrification of urea, ammonia, and proteins. These waste materials are converted to nitrate (NO₃) via nitrification, an aerobic process converting ammonia-nitrogen to nitrate. Denitrification occurs under anoxic conditions (without free oxygen) and involves the biological conversion of nitrate into dinitrogen gas (N₂). N₂O can be an intermediate product of both processes but is more often associated with denitrification (Sheehle and Doorn, 2001).

An overview of treatment methods, wastewater composition, and sources of CH₄ emissions for domestic and industrial wastewater systems is provided below, followed by a discussion of N₂O emissions.

Domestic Wastewater

The process of treating domestic wastewater (sewage) involves three major phases. First, the wastewater collected at a centralized WWTP goes through a primary treatment phase. During this phase, large solids are removed through a filtration process where grit is removed and oxygen is added. Next, the wastewater enters a primary clarifier that removes almost 95 percent of settleable solids. This process takes approximately 30 minutes to an hour, and the initial biodegradation by microorganisms begins. Primary sludge is separated from the effluent at this stage. During this process, wastewater is generally aerated ensuring that the decomposition of the organic matter occurs in an aerobic environment.

Following the primary treatment, it is common to subject the remaining effluent to a secondary treatment. During this phase, the effluent undergoes bio-oxidation through an aerobic process in which aerobic microorganisms break down any remaining organic solids. In the secondary treatment, the effluent is passed through a trickling filter or aeration basin for approximately 4 to 6 hours. Next, the remaining effluent moves into a final clarifier where further biodegradation can occur. This secondary treatment produces additional secondary sludge (biomass). Following the secondary treatment, the effluent is released to a receiving stream.

The sludge (biomass) produced during the primary and secondary phases of treatment is then combined and moved into an encapsulated silo-like digester where it undergoes an anaerobic decomposition process using microorganisms that continue to break down the organics. The digester comprises a holding tank, a gas capture system, and a heating element. Over a period of time (weeks), microorganisms break down the large organic molecules in the feed sludge. Still smaller organisms convert this organic material into CH_4 and CO_2 . On average, 40 to 45 percent of feed sludge is converted to CH_4 and CO_2 during the process. The CH_4 produced is closely monitored for safety concerns and then combusted either in the form of a flare or used to generate heat required during this process. The remaining sludge is sent to landfills.

Industrial Wastewater

Industries producing large volumes of wastewater and industries with high organic COD wastewater load are likely to have significant CH_4 emissions. In the United States, the meat and poultry, pulp and paper, and produce (i.e., fruits and vegetable) industries are the largest sources of industrial wastewater and contain high organic COD. These industries are also considered CH_4 -emitting industries because they employ either shallow lagoons or settling ponds in their treatment of wastewater, which promotes anaerobic degradation.

The meat and poultry industry in the United States has been identified as a major source of CH_4 emissions because of its extensive use of anaerobic lagoons in sequence to screening, fat traps, and dissolved air flotation. It is estimated that 77 percent of all wastewater from the meat and poultry industry degrades anaerobically (USEPA, 1997a).

Treatment of industrial wastewater from the pulp and paper industry is similar to the treatment of municipal wastewater. Treatment in this industry generally includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids. Anaerobic conditions are most likely to occur during lagooning for storage, settling, and biological treatment (secondary treatment). During the primary treatment phase, lagoons are aerated to reduce anaerobic activity. However, the size of these lagoons makes it possible for zones of anaerobic degradation to take place. Approximately half of the initial COD remains following the primary treatment. This remaining COD is passed into a secondary treatment phase where anaerobic degradation is more likely to take place. The USEPA estimates that 25 percent of COD in secondary treatment lagoons degrades anaerobically (USEPA, 1997b).

The fruit, vegetable, and juice-processing industries generate large amounts of wastewater. The treatment of wastewater from these industries generally includes screening, coagulation/settling, and biological treatment (lagooning), while effluent is typically discharged into municipal sewer system. Anaerobic degradation can occur within the lagoons during biological treatment. In the United States it is assumed that these lagoons are intended for aerobic operation, but during peak seasonal usage, anaerobic conditions may occur. The USEPA estimates that approximately 5 percent of wastewater organics degrade anaerobically (Sheehle and Doorn, 2001).

N₂O from Wastewater

The two most significant sources of N₂O identified in the United States are emissions from wastewater treatment processes and emissions from effluent discharge into aquatic environments. IPCC assumes that nitrogen disposal associated with land disposal, subsurface disposal, and domestic wastewater treatment are negligible as sources of N₂O emissions. Generally countries use the IPCC methodology (IPCC, 2000) for estimating national emissions from wastewater. However, current methodologies do not allow for a complete estimate of N₂O emissions. As a result, N₂O baselines reported in this chapter represent the human sewage component only; no methodology exists to estimate N₂O emissions from industrial wastewater.

The remainder of this chapter discusses the activity data and emissions factors used to develop baseline emissions and CH₄ MACs for wastewater systems. The chapter concludes with a discussion of uncertainties and limitations.

III.2.2 Baseline Emissions Estimates

CH₄ generation occurs as organic matter undergoes decomposition in anaerobic conditions. However, CH₄ generation varies widely depending on waste management techniques. Specifically engineered environments can increase the CH₄ generation rates.

The quantity of CH₄ generated can be expressed in terms of several key activity and emissions factors:

Domestic Wastewater

$$CH_4 \text{ Generation} = (POP) * (BOD) * (PAD) * (CH_4P) \quad (2.1)$$

where

POP = total population,

BOD = production of BOD per capita per year,

PAD = percentage of BOD anaerobically digested per year, and

CH₄P = CH₄ generation potential per kg of BOD.¹

Industrial Wastewater

$$CH_4 \text{ Generation} = (IP) * (COD) * (PAD) * (CH_4P) \quad (2.2)$$

¹ IPCC emissions factor of 0.6 kilogram CH₄ per kilogram of BOD, cited in the USEPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2002*.

where

- IP = industry production,
- COD = production of COD per unit of output,
- PAD = percentage of COD anaerobically digested per year, and
- CH₄P = CH₄ generation potential per kg of COD.²

III.2.2.1 Activity Factors

Activity factors determine the quantity of wastewater produced and the intensity of organic content (see explanatory note 2). Domestic wastewater production is related to the population size. The population size, in conjunction with the level of organic waste present in the wastewater (BOD), determines a country's CH₄ generation potential. The per capita production of BOD may vary over time or by country depending on a population's consumption preferences.

Industrial wastewater generation is based largely on the annual product output from major wastewater-producing industries, including meat and poultry packing; pulp and paper manufacturing; and vegetable, fruits, and juices processing. Differences in production processes and recycling practices can influence the COD per unit of production in these industries.

N₂O production is typically estimated using an activity factor of annual per capita protein consumption (kilograms per year). However, it has been suggested that this factor alone underestimates the actual amount of protein entering wastewater treatment systems. Food (waste) that is not consumed is often washed down the drain using garbage disposals. In addition, laundry water can contribute to nitrogen loadings. For these reasons, multipliers are commonly applied to the annual per capita protein consumption activity factor to account for these other sources of nitrogen loading.

Historic Activity Data

Wastewater production is directly related to a country's domestic population and industrial production of select industries. Population growth rates are traditionally higher in developing countries, while more industrialized countries have recently tended to experience smaller increases in population over time. Along with population growth, production of BOD per capita has also been growing, which means that more organic material is present in wastewater. Increases in BOD per capita can result from various economic improvements, which could lead to a change in the availability of food types and consumption preferences.

Industrial growth rates and treatment practices differ by country. Whereas most developed and developing countries have thriving meat and poultry and produce industries, differences exist in the local regulation and treatment practices. Developing countries are more likely to employ lagoons or settling ponds in their treatment of industrial waste, which promotes anaerobic degradation.

Projected Activity Data

Both domestic and industrial wastewater production are expected to increase in the future as populations continue to grow and key industries continue to expand.

² IPCC emissions factor of 0.25 kilogram CH₄ per kilogram of COD, cited in the USEPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2002*.

III.2.2.2 Emissions Factors and Related Assumptions

The primary determinants of wastewater emissions factors are

- CH₄ generation potential per unit of BOD or COD and
- the percentage of BOD or COD that degrades in anaerobic conditions.

CH₄ generation potential per unit of BOD or COD is likely to remain constant because this is a measure of chemical potential, not the result of varying preferences. However, wastewater management practices vary across cities and countries, affecting the percentage of BOD or COD that degrades under anaerobic conditions. Even for managed systems, differences in operations and maintenance can result in unintended anaerobic conditions that lead to additional CH₄ emissions.

Historical Emissions Factors

A CH₄ generation factor of 0.6 kilogram CH₄ per kilogram BOD is provided in the IPCC Good Practice Guidance (IPCC, 2000) for domestic wastewater. This generation factor is also applied to the pulp and paper and meat and poultry industries. A CH₄ generation factor of 0.4 kg CH₄ per kilogram BOD is applied to the fruit, vegetable, and juice-processing industries. This generation factor represents the potential CH₄ generation from a given unit of BOD, assuming that a unit of BOD degrades under anaerobic conditions.

Most developed countries have adopted municipal wastewater treatment practices that prevent the formation of anaerobic conditions in managing and treating wastewater. Developing countries have traditionally employed wastewater management practices that foster controlled anaerobic environments where the CH₄ is captured for flaring or direct use. Settling ponds that are open to the atmosphere are typically aerated to promote the production of CO₂ as opposed to CH₄. However, in developing countries, industries, such as the pulp and paper or meat and poultry, are less likely to have adopted practices to prevent anaerobic degradation of COD in wastewater.

Projected Emissions Factors

Projected emissions factors from wastewater are expected to follow historic trends. The CH₄ generation potential per unit of BOD will remain constant over time. Improvements to wastewater management practices are projected to occur with increased GDP. These improvements may result in decreased baseline emissions for developing countries. As developing countries adopt better management practices, their baseline emissions will approach the baselines of developed countries with established wastewater infrastructure already in place. Overall, reductions in CH₄ emissions factors from wastewater will occur because of improvements in wastewater management and treatment.

III.2.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions from wastewater. As shown in Equations (2.1) and (2.2), the amount of CH₄ generated each year from wastewater is determined by a country's population, the per capita production of BOD or COD (in the industry), and the percentage of BOD that degrades under anaerobic conditions.

Historical Emissions Estimates

Tables 2-1 and 2-2 provide emissions by country for CH₄ and N₂O. Historically, China and India have the largest baseline CH₄ and N₂O emissions from wastewater. China and India are the two most populous countries in the world with 1.3 and 1.1 billion people, respectively, in 2002 (World Bank, 2005). Their large populations in highly concentrated urban areas, combined with limited infrastructure for

Table 2-1: CH₄ Emissions from Wastewater by Country: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
India	81.8	89.7	97.6
China	94.4	99.7	104.2
United States	24.9	29.9	34.3
Indonesia	18.0	19.5	20.9
Brazil	18.0	19.3	20.7
Pakistan	10.9	12.2	14.0
Bangladesh	10.4	11.7	13.0
Mexico	10.0	11.0	11.9
Nigeria	6.8	7.9	9.0
Philippines	6.2	7.0	7.7
Viet Nam	6.7	7.4	8.0
Iran	6.0	6.6	7.2
Turkey	5.7	6.3	6.8
Russian Federation	9.4	9.4	9.3
Ethiopia	3.9	4.5	5.1
Rest of the world	132.8	141.7	152.7
World Total	445.9	483.8	522.5

Source: USEPA, 2006.

Table 2-2: N₂O Emissions from Wastewater by Country: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
China	17.6	18.5	19.4
United States	13.0	14.2	15.6
Brazil	3.7	3.7	4.0
Pakistan	1.8	2.0	2.3
Indonesia	2.1	2.3	2.5
Russian Federation	3.7	3.6	3.4
India	2.0	2.2	2.4
Germany	2.2	2.2	2.2
Nigeria	1.0	1.1	1.3
Iran	1.3	1.4	1.6
Mexico	1.3	1.4	1.6
Bangladesh	0.9	1.1	1.2
Saudi Arabia	0.7	0.8	0.9
Viet Nam	1.0	1.1	1.2
Egypt	0.9	1.0	1.1
Rest of the world	27.4	28.4	30.3
World Total	80.7	85.1	90.8

Source: USEPA, 2006.

handling wastewater, result in substantial emissions. Similar conditions exist in Cambodia and Indonesia where densely populated areas produce significant CH₄ emissions.

Projected Emissions Estimates

Worldwide CH₄ emissions from wastewater are expected to increase in both developed and developing countries because of expanding populations and increases in GDP. Tables 2-3 and 2-4 list projected baseline emissions by country for CH₄ and N₂O. India is projected to replace China as the world's leading emitter of wastewater CH₄. The World Bank projects India's average annual growth rate in population of 1.2 percent over the next 10 years, while China's is projected to be 0.6 percent over the same time period (World Bank, 2005). Although both countries' GDP is projected to increase over time, the most influential factor in determining each country's baseline will be the extent to which these countries improve their wastewater management practices.

III.2.3 Emissions Reductions from Wastewater

Components of abatement options for the wastewater sector include the incremental addition of CH₄ mitigation equipment not already included in the initial construction of a municipal wastewater treatment plant. This section discusses opportunities for emissions reductions beyond existing baseline practices qualitatively but, because of data limitations, does not attempt to model MACs.

III.2.3.1 Abatement Option Opportunities

We describe two approaches to reducing CH₄ emissions from wastewater following the implementation of municipal infrastructure:

- improved wastewater treatment practices (domestic and industrial) and
- anaerobic digester with collection and flaring or cogeneration.

Improved wastewater treatment practices include reducing the amount of organic waste anaerobically digested. This reduction can be achieved through improved aeration and/or the scaling back of the use of stagnant settling lagoons. Costs for improving treatment practices vary widely based on the technology applied and specific characteristics of the wastewater. Improvements to existing wastewater treatment practices assume that infrastructure is already in place and that the cost of any improvements would represent the incremental addition of technology as a capital improvement or increases in O&M costs.

Anaerobic digesters can be flared or the CH₄ used for cogeneration to reduce CH₄ emissions from biomass or liquid effluents with high organic content. The IPCC estimates construction costs for anaerobic digesters to be \$0.1 to \$3 million (IPCC, 1996b). This estimate includes the construction of a collection system and either a flare or a utilization system. IPCC estimates annual O&M costs for this type of system at between \$10,000 and \$100,000, assuming wastewater flows of 0.1 to 100 million gallons (400 to 0.4 x 10⁶ m³) per day (IPCC, 1996b).

Table 2-3: Projected Baseline CH₄ Emissions from Wastewater by Country: 2005–2020 (MtCO₂eq)

Country	2005	2010	2015	2020
India	105.4	112.7	119.1	125.0
China	108.0	111.7	115.3	118.3
United States	35.2	36.1	37.0	37.8
Indonesia	22.2	23.5	24.7	25.9
Brazil	22.0	23.2	24.4	25.5
Pakistan	15.9	18.0	20.2	22.6
Bangladesh	14.5	15.9	17.4	18.8
Mexico	12.8	13.6	14.4	15.1
Nigeria	10.3	11.6	13.1	14.6
Philippines	8.5	9.2	9.8	10.3
Viet Nam	8.5	9.0	9.6	10.2
Iran	7.7	8.2	8.9	9.5
Turkey	7.3	7.7	8.1	8.5
Russian Federation	9.0	8.7	8.5	8.3
Ethiopia	5.8	6.5	7.3	8.2
Rest of the world	165.2	178.3	192.2	206.4
World Total	558.1	594.0	629.9	665.0

Source: USEPA, 2006.

Table 2-4: Projected Baseline N₂O Emissions from Wastewater by Country: 2005–2020 (MtCO₂eq)

Country	2005	2010	2015	2020
China	20.1	20.8	21.5	22.0
United States	15.7	15.9	16.1	16.3
Brazil	4.2	4.5	4.7	4.9
Pakistan	2.6	2.9	3.3	3.7
Indonesia	2.6	2.8	2.9	3.0
Russian Federation	3.3	3.2	3.1	3.0
India	2.5	2.7	2.9	3.0
Germany	2.2	2.2	2.2	2.2
Nigeria	1.5	1.7	1.9	2.1
Iran	1.7	1.8	1.9	2.1
Mexico	1.7	1.8	1.9	2.0
Bangladesh	1.3	1.4	1.6	1.7
Saudi Arabia	1.1	1.2	1.4	1.6
Viet Nam	1.3	1.4	1.5	1.6
Egypt	1.2	1.3	1.4	1.5
Rest of the world	31.9	33.4	35.0	36.5
World Total	95.0	99.1	103.2	107.2

Source: USEPA, 2006.

III.2.3.2 Uncertainties and Limitations

Uncertainty and limitations persist despite attempts to incorporate all publicly available information on international wastewater sectors. Limited information on the wastewater systems of developing countries increases this uncertainty. Additional information would improve the accuracy of baseline emissions projections.

- **BOD Production Rates:** Improved information on specific population diets and consumption habits would greatly improve the analyst's ability to calculate baseline emissions.
- **Country-Specific Waste Management Practices:** Improved documentation of wastewater management practices would allow deviations from the normal assumption, allowing country-by-country estimates of percentage of BOD undergoing anaerobic degradation.
- **Improved Cost Data:** Improved documentation of wastewater CH₄ abatement options and their cost components would improve the analyst's ability to estimate baseline reductions given some estimate of market penetration.

III.2.4 Summary

The data discussed in this chapter demonstrate that wastewater is a significant source of greenhouse gas emissions. However, policy approaches directly targeted at mitigating CH₄ emissions from wastewater are limited, and no specific abatement options are presented as part of the analysis in this chapter. Several factors contribute to difficulties in developing MACs for wastewater abatement options.

The primary factor for determining emissions from the wastewater sector (in terms of CH₄ emissions per BOD) is the type of treatment system employed to manage the waste. Centralized, managed treatment facilities can control anaerobic environments and have a greater potential to capture and use CH₄. Because most centralized systems automatically either flare or capture and use CH₄ for safety reasons, "add-on" abatement options do not exist. As a result, potential emissions reductions depend on large-scale structural changes in waste management practices. In contrast, smaller decentralized systems have less control over the share of aerobic versus anaerobic decomposition and have few feasible options for capturing CH₄.

At issue is that overriding economic and social factors influence wastewater treatment practices throughout the world. The benefits of installing a wastewater system in a developing country for the purpose of disease reduction greatly outweigh potential benefits associated with CH₄ mitigation. This is not to say that CH₄ mitigation is not one of many factors to be potentially considered in selecting wastewater treatment systems. However, because of the scope of the costs and benefits of the investment decision, it would be misleading to imply that potential carbon prices (reflected in MACs) would be the driving force behind investment decisions that influence CH₄ emissions from wastewater.

III.2.5 References

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Explanatory Notes

1. Assuming a global warming potential (GWP) value of 310.
2. The wastewater treatment practices that determine the share of BOD that degrades under anaerobic conditions are included in the emissions factor discussion.

Section III: Waste Sector Appendixes

Appendixes for this section are available for download from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

IV. Industrial Processes

This section presents international emissions baselines and marginal abatement curves (MACs) for 11 industrial sources. Each chapter in this section addresses one of these sources. These sources include nitrous oxide (N₂O) emitted during nitric and adipic acid production; fluorinated gases that are used as substitutes for ozone-depleting substances (ODSs); and high-global warming potential (GWP) gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) from several industrial sources. MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can be downloaded in spreadsheet format from the U.S. Environmental Protection Agency (USEPA) Web site at <<http://www.epa.gov/nonco2/econ-inv/international.html>>.

The Section IV—Industrial Processes chapters are organized as follows:

Nitric Oxide

IV.1 N₂O Emissions from Nitric and Adipic Acid Production

Fluorinated Gases Used as Substitutes for ODSs

IV.2 HFC Emissions from Refrigeration and Air-Conditioning

IV.3 HFC, HFE, and PFC Emissions from Solvents

IV.4 HFC Emissions from Foams

IV.5 HFC Emissions from Aerosols

IV.6 HFC Emissions from Fire Extinguishing

High-GWP Gases from Industrial Processes

IV.7 PFC Emissions from Aluminum Production

IV.8 HFC-23 Emissions from HCFC-22 Production

IV.9 PFC and SF₆ Emissions from Semiconductor Manufacturing

IV.10 SF₆ Emissions from Electric Power Systems

IV.11 SF₆ Emissions from Magnesium (Mg) Production

IV. Industrial Processes Overview

This section presents international emission baselines and MACs for twelve sources of various greenhouse gases, including N₂O, HFCs, PFCs, and SF₆. These sources include production of nitric and adipic acid, which emit N₂O; production of aluminum, magnesium, semiconductors, and HCFC-22, which emit PFCs, SF₆, and HFCs; and use of electrical equipment in electric power systems, which emits SF₆. In addition to the industrial sectors, this section also includes emissions estimates and MACs for fluorinated gases (generally HFCs) that are used as substitutes for ODSs.

While a single set of baseline emissions estimates is presented for most industrial processes covered in this section, five subsectors have dual baselines and MACs. These processes are the production of aluminum, semiconductors, Mg, and HCFC-22, and the use of electrical equipment. For all five of these industries, clearly defined, industry-specific global or regional emissions reduction goals have been announced. First, in response to concerns regarding the high GWPs and long lifetimes of their emissions, the global aluminum, semiconductor, and Mg industries have committed to reduce future emissions by substantial percentages. Second, users (and, in some cases, manufacturers) of electrical equipment in Japan, Europe, and the United States have committed to reduce emissions in those countries and regions. Finally, HCFC-22 producers in several developing countries have agreed to host mitigation projects funded by developed countries under the Clean Development Mechanism (CDM) of the Kyoto Protocol. The HFC-23 abatement projects considered in this analysis are either registered or are in the process of being registered in the CDM pipeline. (HCFC-22 producers in developed countries are also continuing to reduce emissions.) These global and regional emissions reduction goals are summarized in the table below.

Table: Global and Regional Emissions Reduction Commitments

Industry	Global Industry Association, Region, or Country	Percentage of World Production/Emissions in 2003	Goal
Semiconductor manufacturing	World Semiconductor Council	85%	Reduce fluorinated emissions to 90% of 1995 level by 2010
Mg production	International Magnesium Association	80% of the magnesium industry is outside of China; about 80% of global SF ₆ emissions	Phaseout SF ₆ use by 2011
Aluminum production	International Aluminum Institute	70% (but goal applies to entire industry)	Reduce PFCs/ton of aluminum by 80% relative to 1990 levels by 2010
Electrical equipment (use)	EU-25+3, Japan, and United States	40% of use emissions	Country-specific reductions from 2003 totaling 2.5 MtCO ₂ eq, or 15% of these countries' 2003 emissions from use
HCFC-22	China, India, Korea, and Mexico	65% of emissions	CDM projects totaling 55 MtCO ₂ eq, or 63% of these countries' 2010 emissions

The first scenario presented in this report, called the “technology-adoption baseline,” is based on the assumption that these industries will achieve their announced global or regional emissions reduction goals for the year 2010. The second scenario, called the “no-action baseline,” is based on the assumption that emissions rates will remain constant from the present onward in these industries.

The USEPA believes that actual future emissions are likely to be far closer to those envisioned in the technology-adoption baseline than those envisioned in the no-action baseline. Since 1990, all five industries have already made great progress in reducing their emissions rates, and research is continuing into methods to further reduce those rates. Nevertheless, additional actions will be required to actually realize additional reductions. These actions range from process optimization and chemical recycling to chemical replacement. In some cases, the actions are estimated to carry net private costs; in others, net private benefits.

The MACs for the technology-adoption baseline have been adjusted to reflect the implementation of some options in the baseline. When an option is assumed to be adopted in the baseline, the emissions stream to which that option is applied in the MAC is correspondingly decreased, so that options that are fully implemented in the technology-adoption baseline are not present in the technology-adoption MAC at all.

Depending on the context, either set of baselines and MACs may be of interest. For example, analysts interested in the incremental costs of reducing emissions below the levels anticipated in current global industry commitments can use the technology-adoption baseline and the associated MACs. On the other hand, analysts interested in the future costs of achieving the currently planned industry reductions can use the no-action baseline and the associated MACs. The difference between the two baselines is itself of interest, demonstrating that the industry commitments are likely to avert very large emissions.

It should be noted that the USEPA modeled only those reduction efforts that had been clearly announced and quantified on an industry-specific basis at the time this report was prepared. This means that even in the technology-adoption baseline, significant reduction opportunities remain in 2010 and 2020, primarily in developing countries. This is particularly true for the HCFC-22 and electric power system industries. In fact, there is a significant probability that many of these emissions will be averted (e.g., by fuller implementation of CDM or other reduction efforts). However, the precise extent of additional reduction actions is uncertain. Thus, the technology-adoption baseline reflects only current, quantitative, industry-specific goals.

Past emissions (1990 through 2000) for all five sources are identical under either scenario, but they are provided with both scenarios to provide context for the divergent future trends.

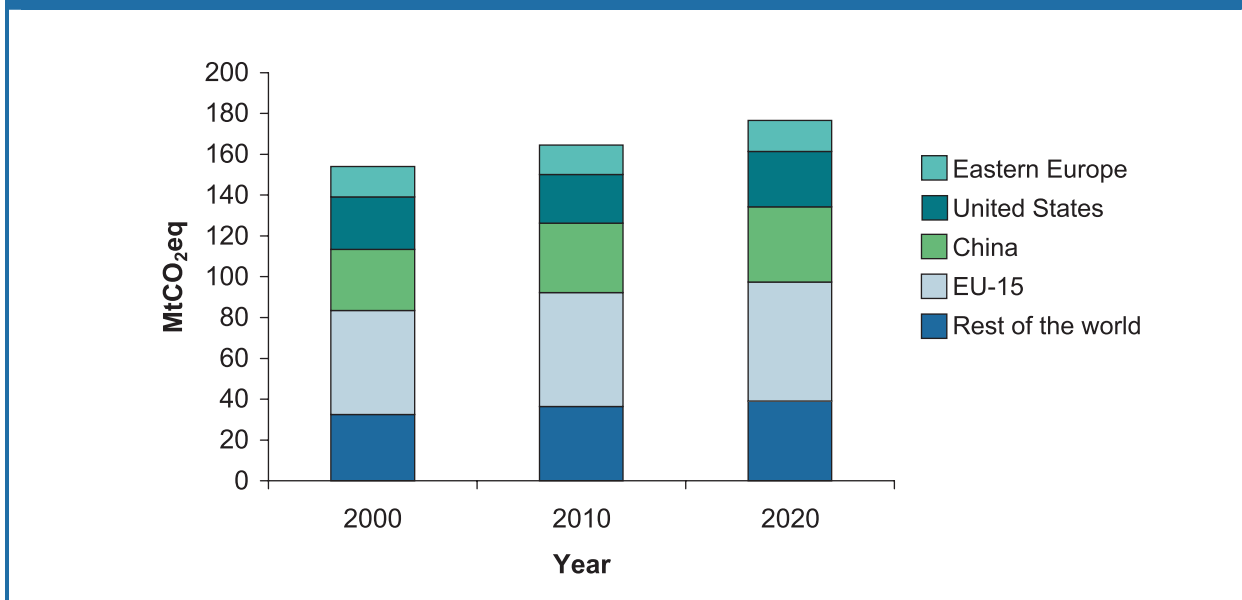
Detailed discussions of the methodology used to develop the baselines for each source can be found in the USEPA (2006) report *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020*.

IV.1 N₂O Emissions from Nitric and Adipic Acid Production

Worldwide N₂O emissions from industrial sources account for more than 154 million metric tons of carbon dioxide (CO₂) equivalent (MtCO₂eq) (USEPA, 2006). The USEPA estimates that emissions from nitric and adipic acid production combined contributed approximately 5 percent of total global N₂O emissions in 2000 (USEPA, 2003). Nitric acid production accounts for 67 percent of N₂O emissions from industrial production, and adipic acid accounts for the remaining 33 percent (USEPA, 2003).

Eastern Europe, the United States, China, and the European Union (EU-15) combined account for 79 percent of total N₂O emissions from industrial production (Figure 1-1). The Intergovernmental Panel on Climate Change (IPCC) reports that the number of nitric acid production plants worldwide is estimated at 250 to 600. The United States is the primary producer of adipic acid, with four production sites alone, accounting for approximately 40 percent of total adipic acid production worldwide (USEPA, 2001). Other countries have at most one adipic acid plant (IPCC, 2000).

Figure 1-1: N₂O Emissions from Industrial Production by Country: 2000–2020



Source: USEPA, 2006.
EU-15 = European Union.

Global N₂O emissions from industrial production sources are expected to grow by approximately 13 percent between 2005 and 2020 (USEPA, 2006), although the percentage distribution of emissions across countries is projected to remain relatively unchanged.

IV.1.1 Introduction

The two major sources of anthropogenic N₂O emissions from industry are production of nitric and adipic acid. These dicarboxylic acids produce N₂O as a by-product of the production process. N₂O is then emitted in the waste gas stream (USEPA, 2001).

IV.1.1.1 Nitric Acid

Nitric acid is an inorganic compound, typically used to make synthetic commercial fertilizer. Nitric acid is also used in the production of adipic acid, explosives, and metal etching and in the processing of ferrous metals. Nitric acid is produced through catalytic oxidation of ammonia (CH_4) at high temperatures, which creates N_2O as a reactionary by-product released from reactor vents into the atmosphere (Mainhardt and Kruger, 2000). IPCC believes that nitric acid production now represents the majority of N_2O emissions from industrial process as a result of implementing abatement technologies at adipic acid plants.

In the United States, the nitric acid industry controls for nitrogen oxides gases using a combination of nonselective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies (USEPA, 2004). The NSCR units destroy nitrogen oxides, but they also destroy N_2O . However, NSCR is considered costly and obsolete at modern plants. NSCR units were commonly installed in production facilities built between 1971 and 1977 (USEPA, 2004). The USEPA reports that NSCR is currently used by approximately 20 percent of the U.S. nitric acid production plants; the majority of the industry uses SCR or extended absorption, neither of which is known to reduce N_2O (USEPA, 2004).

IV.1.1.2 Adipic Acid

Adipic acid is a white crystalline solid used primarily as a component in the production of nylon (nylon 6/6). Adipic acid is also used in the manufacture of low-temperature synthetic lubricants, coatings, plastics, polyurethane resins, and plasticizers and is used to give some imitation foods a “tangy” flavor. Industrial sources report that by 2000, all major adipic acid production plants had implemented abatement technologies and consequently have dramatically reduced N_2O emissions from this source (Mainhardt and Kruger, 2000).

Adipic acid is produced through a two-stage process during which N_2O is generated in the second stage. The first stage of manufacturing usually involves the oxidation of cyclohexane to form cyclohexanone/cyclohexanol mixture. The second stage entails oxidizing this mixture with nitric acid to produce adipic acid. N_2O is produced as a by-product during the nitric acid oxidation stage and potentially is emitted in the waste gas stream (USEPA, 2004). Emissions from this source vary depending on the type of technologies and level of emissions controls employed by a specific facility.

IV.1.2 Baseline Emissions Estimates

N_2O emissions correlate closely with the production of nitric and adipic acid. This section discusses production activity, suggested emissions factors, and the resulting baseline emissions estimates based on publicly available reports.

IV.1.2.1 Activity Factors

Activity factors characterize the intensity of production in these industries, which, when combined with emissions factors, result in an estimated baseline emission.

Historical Activity Data

Nitric Acid

Nitric acid production levels closely follow trends in fertilizer consumption, because of nitric acid’s role as a major component in fertilizer production (Mainhardt and Kruger, 2000). Trends in fertilizer production vary widely across different regions of the world. For example, in Western Europe, because of concerns over nutrient runoff, nitrogen-based fertilizer use has been scaled back. However, in regions

where agriculture accounts for a larger share of the gross domestic product (GDP), such as Asia, South America, and the Middle East, nitrogen-based fertilizer production capacity is increasing (Mainhardt and Kruger, 2000).

The actual number of nitric acid production plants globally is unknown. Previous reports cited by the IPCC have suggested the number to be between 250 and 600. This uncertainty is due to the fact that many nitric acid plants are often part of larger facilities that manufacture products using nitric acid, such as fertilizer and explosives facilities (Mainhardt and Kruger, 2000).

Adipic Acid

Adipic acid is used primarily in the production of nylon. As a result, production of adipic acid is closely correlated with the world's nylon production. Global demand for engineering plastics has increased over time, resulting in major expansion in production capacity in North America and Western Europe and new facilities in the Asia Pacific region. In the United States, adipic acid production increased by approximately 50 percent between 1990 and 2000 (USEPA, 2004).

Global capacity for adipic acid was approximately 2.8 million metric tons in 2003. Table 1-1 lists estimated adipic acid production capacity in 2003 by country. Demand for adipic acid was estimated at 2.21 million metric tons for the same year (*Chemical Week [CW]*, 2003). As a result of this oversupply in the global market, many adipic acid facilities have been operating at an average rate of 85 percent of capacity.

Table 1-1: 2003 Adipic Acid Production Capacity (Thousands of Metric Tons/Year)

Country	Adipic Acid Capacity
United States	1,002.0
Germany	408.0
France	320.0
United Kingdom	220.0
Canada	170.0
South Korea	135.0
China	127.0
Japan	122.0
Singapore	114.0
Brazil	80.0
Italy	70.0
Ukraine	56.0
World Total	2,824.0

Source: *CW*, 2003.

Projected Activity Data

Nitric Acid

Nitric acid production is expected to increase over time (Mainhardt and Kruger, 2000). The Global Emissions Report, from which the emissions projections came, used data that did not report specific country activity. Projected production data for nitric acid production were unavailable at the time of publication of this report.

Adipic Acid

Industrial demand for adipic acid is expected to continue to increase by approximately 2 percent per year between 2003 and 2008 (CW, 2003). Nylon 6,6 accounts for approximately 70 percent of demand for adipic acid. The demand for fiber-grade nylon 6,6 is projected to grow by 1 percent per year, whereas engineering-grade nylon 6,6 is projected to grow by 4.5 percent per year. The dramatic growth in engineering-grade nylon is a result of its increased use as a substitute for metal in under-the-hood automotive applications (CW, 2003).

IV.1.2.2 Emissions Factors and Related Assumptions

Nitric Acid

The IPCC reports that N₂O emissions factors for nitric acid production remain relatively uncertain, because of a lack of information on manufacturing processes and emissions controls. The emissions factor is estimated, based on the average amount of N₂O generated per unit of nitric acid produced, combined with the type of technology employed at a plant. The IPCC uses a default range of 2 to 9 kilograms N₂O per ton of nitric acid produced. As a result, emissions factors for nitric acid production plants may vary significantly based on the type of technology employed at the plant. For example, NSCR is very effective at destroying N₂O, whereas alternative technologies such as SCR and extended absorption do not reduce N₂O emissions.

In the United States, a weighted average of 2 kilograms N₂O per ton nitric acid is used for plants using NSCR systems, and 9.5 kilograms N₂O per ton nitric acid is used for plants not equipped with NSCR. Table 1-2 lists the reported emissions factors by IPCC in the *Revised 1996 Reference Manual*.

Table 1-2: IPCC Emissions Factors for Nitric Acid Production in Select Countries

Country	Nitric Acid Emissions Factors
United States	2.0–9.0 ^a
Norway—modern, integrated plant	< 2.0
Norway—atmospheric-pressure plant	4.0–5.0
Norway—medium-pressure plant	6.0–7.5
Japan	2.2–5.7

Source: IPCC, 1996.

^a Emissions factors up to 19 kilograms per ton nitric acid have been reported for plants not equipped with NSCR technology.

The IPCC points out that potential emissions factors as high as 19.5 kilograms N₂O per ton of nitric acid have been estimated in previous reports. In addition, estimates of 80 percent of the nitric acid plants worldwide do not employ NSCR technology, which makes it more likely that the default range of potential emissions factors provided by the IPCC greatly underestimates the true emissions baselines (Mainhardt and Kruger, 2000).

Adipic Acid

The IPCC provides countries with a default emissions factor of 300 kilograms N₂O per ton of adipic acid produced. This emissions factor assumes that no N₂O control system is in place. This factor was developed using laboratory experiments measuring the reactionary stoichiometry for N₂O generation during the production of adipic acid (Mainhardt and Kruger, 2000). This emissions factor has been supported by some selected measurement at industrial plants. IPCC recommends using plant-specific data for those plants with abatement controls already in place (IPCC, 1996).

IV.1.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions from the industrial process sector for the production of nitric and adipic acid.

Historical Emissions Estimates

Table 1-3 lists historical N₂O emissions by country. Worldwide N₂O baseline emissions from nitric and adipic acid production decreased by 28 percent between 1990 and 2000. The United Kingdom, Germany, and Canada experienced the largest declines in baseline emissions, with 88 percent, 84 percent, and 77 percent declines, respectively, over the same 10-year period. However, countries such as China, Japan, South Korea, and India saw baseline increases of 54, 29, 25, and 29 percent, respectively.

Table 1-3: N₂O Emissions from Nitric and Adipic Acid Production: 1990–2000 (MtCO₂eq)

Country	1990	1995	2000
China	19.6	27.5	30.1
United States	33.1	37.1	25.6
France	24.1	26.2	11.5
South Korea	5.7	6.1	7.1
Italy	6.7	7.1	7.8
Netherlands	7.6	7.5	7.1
Brazil	2.5	4.3	5.0
United Kingdom	29.3	19.0	6.3
Germany	23.5	25.0	5.5
Belgium	3.9	4.6	4.6
Japan	7.4	7.4	4.2
Poland	5.0	4.9	4.3
India	2.4	2.8	3.0
Bulgaria	2.3	1.9	1.3
Romania	8.9	3.6	2.9
Rest of the world	41.4	35.0	27.5
World Total	223.4	220.1	154.0

Source: USEPA, 2006.

Projected Emissions Estimates

Table 1-4 lists combined projected N₂O baseline emissions from nitric and adipic acid by country. Worldwide total N₂O emissions from nitric and adipic acid are projected to increase by approximately 16 percent between 2005 and 2020. The United States, South Korea, and Brazil are expected to experience the largest increase in baseline emissions, with 28, 22, and 22 percent, respectively, between 2005 and 2020.

Nitric Acid

Emissions from nitric acid production are expected to increase by 13 percent between 2000 and 2020, because of an expanding market for synthetic fertilizer (see explanatory note 1). Brazil, Mexico, and India are projected to increase their N₂O baseline emissions by 29, 25, and 22 percent, respectively, from nitric acid production (USEPA, 2006).

Table 1-4: Projected N₂O Baseline Emissions from Nitric and Adipic Acid Production: 2005–2020 (MtCO₂eq)

Country	2005	2010	2015	2020
China	32.0	34.1	35.5	37.0
United States	22.4	23.9	25.5	27.2
India	3.2	3.4	3.6	3.8
France	12.9	14.3	14.4	14.5
Italy	8.2	8.6	9.1	9.6
Brazil	5.5	6.1	6.4	6.7
Netherlands	7.5	7.7	8.1	8.3
South Korea	7.9	8.7	9.1	9.6
United Kingdom	6.3	6.3	6.3	6.3
Germany	5.7	5.9	6.1	6.2
Belgium	4.7	4.9	5.1	5.2
Japan	4.6	4.6	4.8	5.0
Poland	4.3	4.3	4.3	4.3
Bulgaria	2.3	2.7	2.9	3.4
Ukraine	2.4	2.4	2.4	2.4
Rest of the world	26.5	26.7	26.9	27.2
World Total	156.5	164.6	170.4	176.6

Source: USEPA, 2006.

Adipic Acid

Emissions from adipic acid production are projected to increase by approximately 40 percent between 2000 and 2020, reflecting increased demand for engineering nylon (see explanatory note 1). Southeast Asia, Brazil, and Mexico are projected to experience 45, 44, and 39 percent increases, respectively, in baseline emissions of N₂O.

IV.1.3 Cost of N₂O Emissions Reductions from Industrial Processes

N₂O emissions can be reduced by optimizing the catalytic oxidation of CH₄ to nitrogen oxide or by decomposing N₂O either during the processing of nitric acid or in the tail gas. Currently, N₂O reduction technologies include extending the reaction process through thermal decomposition in the reaction chamber, reducing N₂O through catalytic reduction in the reaction chamber, using NSCR or SCR in the upstream tail gas expander, or using SCR in the downstream tail gas expander (Smit, Gent, and van den Brink, 2001). Each of the technologies has advantages and disadvantages, including the amount of utilities required to run the technology, downtime at the plant for installation, consumption of the reducing agent, and retrofit limitations at existing plants. Depending on the technology, reduction efficiencies can range from 70 percent to 98 percent and costs can range from \$0.52 to \$9.30 per tCO₂eq for new installations and \$0.86 to \$9.48 per tCO₂eq.

Abatement options for the nitric and adipic acid sectors at the time of the Energy Modeling Forum 21 (EMF-21) analysis were relatively limited. However, more recent innovations have proven effective options for abating N₂O at nitric acid production plants. The data presented in this report use an average reduction and cost of NSCR and SCR technologies. Therefore, the reduction potential is at the high end of the reduction range and the costs are on the lower end of the range. Table 1-5 summarizes cost and emissions reductions for the abatement options included in the EMF-21 analysis (USEPA, 2003).

Table 1-5: Cost of Reducing N₂O Emissions from Industrial Processes

Technology	Breakeven Price (\$/tCO ₂ eq)	Emissions Reduction (% from baseline) ^a	Emissions Reduction in 2010 (MtCO ₂ eq)	Emissions Reduction in 2020 (MtCO ₂ eq)
Assuming a 10% discount rate and 40% tax rate				
Nitric Acid Sector^b				
Grand Paroisse—high-temperature catalytic reduction method	\$2.59	6%	0.05	0.05
BASF—high-temperature catalytic reduction method	\$2.36	6%	0.05	0.05
Norsk Hydro—high-temperature catalytic reduction method	\$1.99	7%	0.05	0.06
HITK—high-temperature catalytic reduction method	\$2.75	7%	0.06	0.06
Krupp uhde—low-temperature catalytic reduction method	\$2.92	7%	0.06	0.06
ECN—low-temperature selective catalytic reduction with propane addition	\$5.81	7%	0.06	0.06
NSCR ^c	\$4.03	6%	0.05	0.05
Adipic Acid Sector^c				
Thermal destruction	\$0.50	50%	0.21	0.24

Source: USEPA, 2003. Adapted from Nitric Acid and Adipic Acid Sector technology tables in Appendix B.

^a Values represent average percentages across all EMF-21 countries/regions included in the analysis.

^b Based on 10-year lifetime.

^c Based on 20-year lifetime.

IV.1.3.1 Nitric Acid: N₂O Abatement Option Opportunities

High-Temperature Catalytic Reduction Method

This N₂O abatement option has several variations developed by different companies, all involving the decomposition of N₂O into nitrogen and oxygen using various catalysts. The average estimated reduction efficiency is approximately 90 percent. Total capital costs for these abatement technologies range from \$2.18 to \$3.27 per tCO₂eq. Operating and maintenance (O&M) costs vary by country. In the United States, O&M costs can range from \$0.14 to \$0.22 per tCO₂eq. This abatement option has an average technical lifetime of 10 years, yielding a breakeven price of approximately \$0.82 per tCO₂eq.

Low-Temperature Catalytic Reduction Method

Low-temperature catalytic reduction systems work similarly to high-temperature counterparts but do not require heat to decompose the N₂O. This abatement option has a reduction efficiency of 95 percent. Some versions of this abatement option require propane be added to the gas stream before undergoing the reaction process. Total capital cost for this option ranges from \$3.27 to \$3.55 per tCO₂eq. In the United States, O&M costs range from \$0.27 to \$1.91 per tCO₂eq. This option has a technical lifetime of 10 years, yielding a breakeven price of approximately \$0.82 per tCO₂eq.

Nonselective Catalytic Reduction

NSCR uses a fuel and a catalyst to consume free oxygen in the tail gas, converting nitrogen oxides to elemental nitrogen. The gas from the nitrogen oxides abatement is passed through a gas expander for energy recovery, resulting in a reduction efficiency of 85 percent. The process requires additional fuel and emits CO₂. The total capital cost for this option is \$6.27 per tCO₂eq. In the United States, the O&M cost is estimated at \$0.16 per tCO₂eq. NSCR has a technical lifetime of 20 years, yielding a breakeven price of approximately \$1.90 per tCO₂eq.

IV.1.3.2 Adipic Acid: N₂O Abatement Option Opportunities

Thermal Destruction

Thermal destruction is the destruction of off-gases in boilers using reducing flame burners with premixed CH₄ (or natural gas). The system eliminates between 98 percent and 99 percent of N₂O and operates from 95 percent to 99 percent of the time. Total capital costs for thermal destruction are \$0.38 per tCO₂eq. In the United States, O&M costs are estimated to be approximately \$0.16 per tCO₂eq. This abatement option has a technical lifetime of 20 years, yielding a breakeven price of approximately \$0.27 per tCO₂eq.

IV.1.4 Results

This section presents the EMF-21's MAC analysis results.

IV.1.4.1 Data Tables and Graphs

The nitric and adipic baselines are presented in Tables 1-6 and 1-8. Tables 1-7 and 1-9 present percentage reductions for different carbon prices (\$/tCO₂eq) from the emissions baselines for each sector. Figures 1-2 and 1-3 present these results in graphical form. Significant abatement potential is estimated to exist at \$15 per tCO₂eq. It is estimated that there are no “no-regret” options for N₂O nitric or adipic acid production. At a breakeven price of \$15 per tCO₂eq, the percentage abatement is 89 percent for nitric acid and 96 percent for adipic acid, reflecting the relatively high technical potential and low abatement cost for options in these industrial processes. Technology changes have not been incorporated in the abatement potential for N₂O emissions from industrial processes.

IV.1.4.2 Uncertainties and Limitations

Uncertainties and limitations persist despite attempts to incorporate all publicly available information on international sectors. Limited information on the systems of developing countries increases this uncertainty. Additional information would improve the accuracy of baseline emissions projections.

Improved Cost Data

Improved documentation of N₂O abatement options and their cost components would improve the analyst's ability to estimate baseline reductions given some estimate of market penetration.

Improved Manufacturing Data for Nitric Acid

Currently, worldwide nitric acid production is very uncertain because of a lack of good production estimates. In addition, improved data on the types of equipment generally employed by industries and trends in technology adoption in each country would improve the analyst's ability to estimate baseline emissions over time.

Table 1-6: Projected N₂O Emissions from Nitric Acid by Region: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	1.9	1.9	1.8
Annex I	68.0	68.5	71.9
Australia/New Zealand	0.0	0.0	0.0
Brazil	3.4	4.0	4.3
China	20.1	22.1	23.7
Eastern Europe	9.9	9.4	9.7
EU-15	33.8	36.2	37.3
India	2.0	2.2	2.4
Japan	2.8	3.0	3.2
Mexico	0.6	0.7	0.8
Non-OECD Annex I	6.6	6.5	6.8
OECD	66.8	68.4	72.0
Russian Federation	0.2	0.2	0.2
South & SE Asia	0.5	0.5	0.6
United States	17.1	15.5	17.4
World Total	102.6	107.0	113.1

Source: USEPA, 2006.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-7: Percentage Abatement for Nitric Acid for Selected Breakeven Prices (\$/tCO₂eq): 2010–2020

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Australia/New Zealand	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
Brazil	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
China	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
Eastern Europe	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
EU-15	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
India	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
Japan	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
Mexico	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
Russian Federation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
South & SE Asia	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
United States	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%
World Total	0.00%	88.94%	88.94%	88.94%	88.94%	0.00%	88.94%	88.94%	88.94%	88.94%

Source: USEPA, 2003. Adapted from Nitric Acid Sector technology tables in Appendix B.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-8: Projected N₂O Emissions from Adipic Acid by Region: 2000–2020 (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	1.0	1.0	1.0
Annex I	34.1	36.9	40.3
Australia/New Zealand	0.0	0.0	0.0
Brazil	1.7	2.1	2.4
China	10.0	11.9	13.3
Eastern Europe	5.0	5.0	5.4
EU-15	16.9	19.5	20.9
India	1.0	1.2	1.4
Japan	1.4	1.6	1.8
Mexico	0.3	0.4	0.4
Non-OECD Annex I	3.3	3.5	3.8
OECD	33.5	36.8	40.4
Russian Federation	0.1	0.1	0.1
South & SE Asia	0.2	0.3	0.3
United States	8.6	8.4	9.8
World Total	51.4	57.6	63.5

Source: USEPA, 2006.

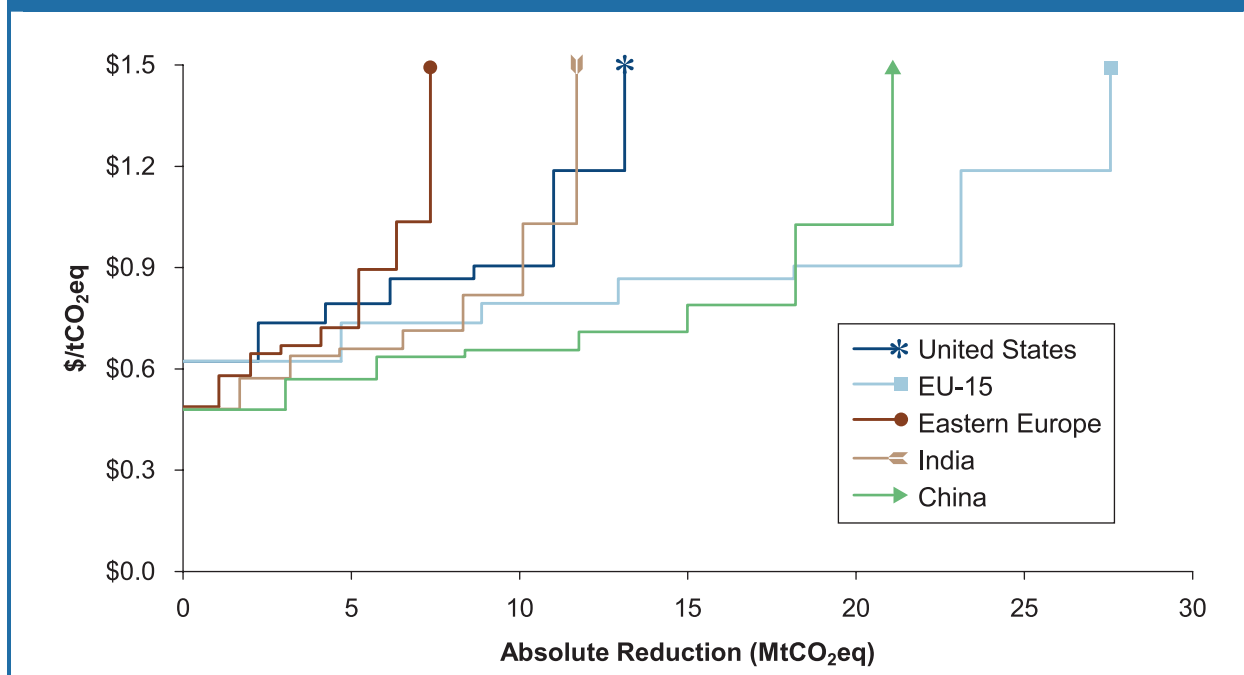
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-9: Percentage Abatement for Adipic Acid for Selected Breakeven Prices (\$/tCO₂eq): 2010–2020

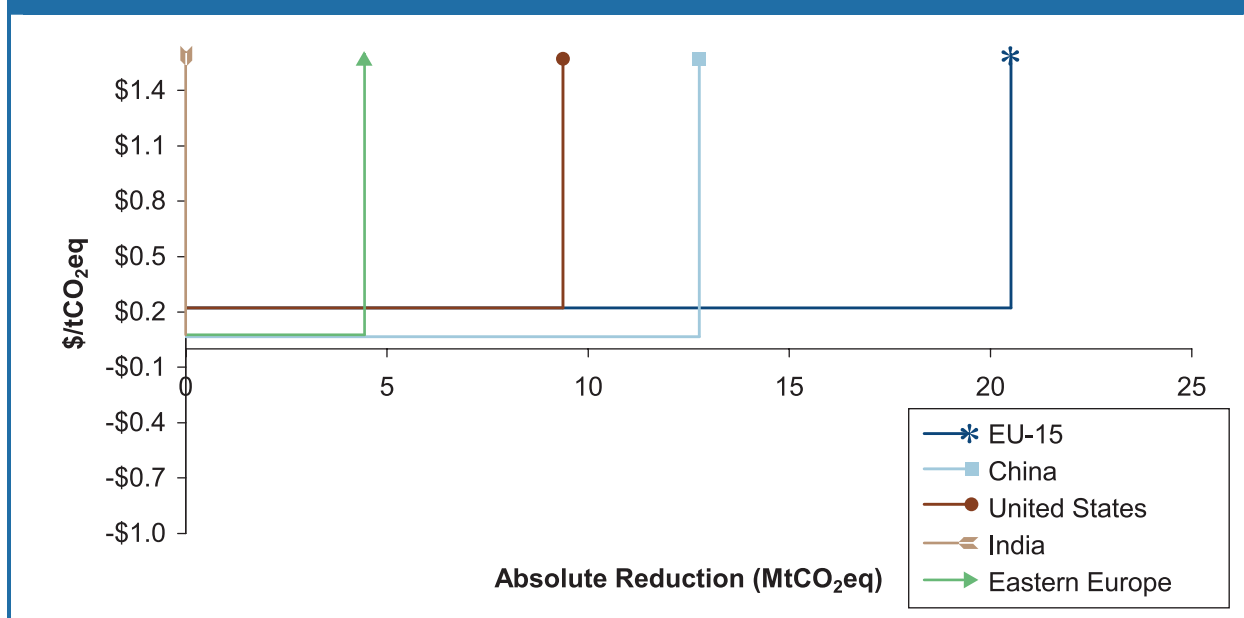
Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Australia/New Zealand	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
Brazil	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
China	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
Eastern Europe	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
EU-15	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
India	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Japan	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
Mexico	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Russian Federation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
South & SE Asia	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
United States	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%
World Total	0.00%	96.00%	96.00%	96.00%	96.00%	0.00%	96.00%	96.00%	96.00%	96.00%

Source: USEPA, 2003. Adapted from Nitric Acid Sector technology tables in Appendix B.

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 1-2: EMF MACs for Top Five Emitting Country/Regions from Nitric Acid Production: 2020

EU-15 = European Union.

Figure 1-3: EMF MACs for Top Five Emitting Country/Regions from Adipic Acid Production: 2020

EU-15 = European Union.

Improved Emissions Factor Estimates

Current emissions factors are the result of laboratory experiments and only a few on-site facility measurements. Additional facility measurements would greatly improve the accuracy of each country's baseline emissions.

IV.1.5 Summary

Adipic acid producers in the United States have already adopted options to mitigate emissions of N₂O. Nitric and adipic acid production will continue to increase, correlating closely with the world's demand for synthetic fertilizers and nylon. However, certain abatement options may mitigate significant portions of a country's baseline if adopted by producers.

IV.1.6 References

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Explanatory Notes

1. Separate emissions estimates for nitric and adipic acid were unavailable for 2005, thus projected percentage changes are presented for 2000 to 2020. Note that individual percentage changes for nitric and adipic acid are not comparable with the total percentage change of 16 percent, which is for 2005 to 2020.

IV.2 HFC Emissions from Refrigeration and Air-Conditioning

IV.2.1 Introduction

A number of HFCs are used in refrigeration and air-conditioning systems and are emitted to the atmosphere during equipment operation and repair. Specifically, emissions occur during product and equipment manufacturing and servicing, and from disposal of equipment and used refrigerant containers. Emissions also occur during equipment operation, as a result of component failure, leaks, and purges. The use of refrigeration and air-conditioning equipment also generates indirect emissions of greenhouse gases (primarily CO₂) from the generation of power required to operate the equipment. In some refrigeration and air-conditioning applications, these indirect emissions outweigh the direct emissions. Therefore, energy efficiency has a major impact on the total greenhouse gas emissions of an application. To the extent possible, both direct and indirect emissions were considered in the refrigeration and air-conditioning analysis; however, options aimed solely at improving energy efficiency rather than abating HFC emissions were not explored in detail. HFCs used in this sector have 100-year GWPs that range from 140 to 11,700; the majority of HFCs used today in the refrigeration and air-conditioning sector have GWPs from 1,300 (i.e., HFC-134a) to 3,300 (i.e., R-507A).

The refrigeration and air-conditioning sector includes eight major end-uses:

- household refrigeration,
- motor vehicle air-conditioning (MVAC),
- chillers,
- retail food refrigeration,
- cold storage warehouses,
- refrigerated transport,
- industrial process refrigeration, and
- residential and small commercial air-conditioning/heat pumps.

Each end-use is composed of a variety of equipment types that have historically used ODSs such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). As the ODS phaseout is taking effect under the Montreal Protocol, equipment is being retrofitted or replaced to use HFC-based substitutes or intermediate substitutes (e.g., HCFCs) that will eventually need to be replaced by non-ozone-depleting alternatives. HCFCs are beginning to be replaced with HFCs or other alternative refrigerants. The eight major end-uses are explained in more detail below.

IV.2.1.1 Household Refrigeration

This end-use consists of household refrigerators and freezers. HFC-134a is the primary substitute for CFC-12 in domestic refrigeration units in the United States and most developing countries, with hydrocarbon (HC) refrigerant, especially isobutane (HC-600a), dominating much of the European market and continuing to grow in market share. HC-600a is also gaining market share in Japan (Kuijpers, 2002). The charge size of a typical household refrigeration unit in the United States has decreased over the past 15 years to about 0.17 kilograms for new HFC-134a units, with sizes even smaller in Europe.¹ HC-600a

¹ Differences in charge sizes are accounted for in the modeling methodology.

systems are about 40 percent smaller than HFC-134a systems. The equipment has an expected lifetime of 20 years. This end-use is one of the largest in terms of the number of units in use; however, because the charge sizes are small and the units are hermetically sealed (and, therefore, rarely require recharging), emissions are relatively low. Thus, the potential for reducing emissions through leak repair is small. In most Annex I countries, where regulations are in place that require the recovery of refrigerant from appliances prior to disposal, the retirement of old refrigerators is not expected to result in significant refrigerant emissions. Refrigerant emissions at disposal from developing countries, where refrigerant recovery is not generally required, are expected to be greater. Emissions from the insulating foam in household refrigerators and freezers are discussed in a separate chapter of this report.

IV.2.1.2 Motor Vehicle Air-Conditioning (MVAC)

This end-use includes the air-conditioning systems in motor vehicles (e.g., cars, trucks, and buses). Currently, the quantity of refrigerant contained in a typical car air conditioner is approximately 1 kilogram—generally from 1 to 1.2 kilograms for vehicles containing CFC-12 systems, and an average of approximately 0.8 kilograms for vehicles containing HFC-134a systems (Atkinson, 2000; European Commission [EC], 2003)—although this varies by car and region (e.g., in Japan, the average amount is about 0.5 kilograms). Because of concerns over the environmental impact of refrigerants, the average charge size of MVACs—as well as associated leak rates—have been reduced over time; this trend is expected to continue. The expected lifetime of MVACs is approximately 12 years. Refrigerant use in this sector is significant because more than 700 million motor vehicles are registered globally (Ward's, 2001). In developed countries, CFC-12 was used in MVACs until being phased out of new cars in 1992 through 1994. Since then, all air conditioners installed in new automobiles use HFC-134a refrigerant. HFC-134a is also used as a retrofit chemical for existing CFC-12 systems (UNEP, 1998).

CFC-12 availability in developing countries and in some developed countries (e.g., the United States) has resulted in its use for servicing older MVACs that were originally manufactured as CFC-12 systems. A variety of refrigerant blends are approved for use in the United States by the USEPA as replacements for CFC-12 in MVACs. However, these blends have not been endorsed by vehicle or system manufacturers. Globally, these blends have captured only a small and declining share of the retrofit market. Some conversions from CFC-12 to pure HCs have been done. However, this is illegal in the United States, and such use in direct expansion systems not designed for a flammable refrigerant can pose safety concerns and is not considered acceptable by much of the global MVAC industry. Climate change concerns associated with the use of HFC-134a resulted in research into and development of other MVAC alternatives. Possible alternatives to HFC-134a systems include transcritical CO₂ systems, hydrocarbons (e.g., in new secondary-loop systems), and HFC-152a systems, all of which are under study and development (SAE, 2003a).

IV.2.1.3 Chillers

Chillers are used to regulate the temperature and reduce humidity in offices, hotels, shopping centers, and other large buildings, as well as in specialty applications on ships, submarines, nuclear power plants, and other industrial applications. The four primary types of chillers are centrifugal, reciprocating, scroll, and screw, each of which is named for the type of compressor employed. Chillers last longer than most air-conditioning and refrigeration equipment. The majority of operating chillers will remain in service for more than 20 years, and some will last 30 years or more. A wide variety of chillers is available, with cooling capacities from 7 kilowatts to over 30,000 kilowatts (RTOC, 2003). The charge size of a chiller depends mostly on cooling capacity and ranges from less than 25 kilograms (reciprocating) to over 2,000 kilograms (centrifugal). HCFC-123 has been the refrigerant of choice as a retrofit option for newer CFC-11 units, and HFC-134a has been the refrigerant of choice as a retrofit option for newer CFC-

12 units. The replacement market for CFC-12 high-pressure chillers and CFC-11 low-pressure chillers is dominated by both HCFC-123 chillers and HFC-134a chillers in developed and developing countries. Following phaseout of the production of HCFCs (in 2030 for developed countries and 2040 for developing countries), recycled, recovered, and reclaimed HCFCs will continue to be used in most countries. This trend is not the case, however, in the European Union (EU-25), where there are restrictions on the use of HCFCs in new equipment, the production of HCFCs is not permitted beyond 2010, and recycled HCFCs may not be reused beyond 2015. In the EU, HFC-134a will be an important option for chillers, but because of its global warming impact, ammonia chillers are being used as an alternative in some countries (Kuijpers, 2002).

Additionally, HFC-245fa is a potential refrigerant for new low-pressure chillers. However, for a variety of reasons, the commercialization of this chiller technology is not likely to occur in the near future, if at all. High-pressure chillers that currently use HCFC-22 will ultimately be replaced by several HFC refrigerant blends and HFC-134a chillers. Likewise, existing CFC-114 chillers have been converted to HFC-236fa or replaced with HFC-134a chillers, for use primarily in specialty applications (e.g., on ships and submarines, and in nuclear power plants) (RTOC, 2003; IPCC/TEAP, 2005).

IV.2.1.4 Retail Food Refrigeration

Retail food refrigeration includes refrigerated equipment found in supermarkets, convenience stores, restaurants, and other food service establishments. This equipment includes small refrigerators and freezers, refrigerated display cases, walk-in coolers and freezers, and large parallel systems. Charge sizes range from 6 to 1,800 kilograms, with a lifetime of about 15 years. Convenience stores and restaurants typically use standalone refrigerators, freezers, and walk-in coolers. In contrast, supermarkets usually employ large parallel systems that connect many display cases to a central compressor rack and condensing unit by means of extensive piping. Because the connection piping can be miles long, these systems contain very large refrigerant charges and often experience high leakage rates.

During the earlier phases of the CFC phaseout in developed countries, the use of HCFC-22 in retail food refrigeration was expanded considerably. Retail food equipment is being retrofitted with HCFC-based blends, although HFC blends are also used as a retrofit refrigerant. The HFC blend R-404A is the preferred refrigerant in new retail food equipment in developed countries, while R-507A is also used extensively in the market (Kuijpers, 2002). In developed countries, both distributed and centralized systems that use HFCs, HCs, ammonia, and CO₂ are being developed (both with and without secondary loops) (Kuijpers, 2002).

IV.2.1.5 Cold Storage Warehouses

Cold storage warehouses are used to store meat, produce, dairy products, and other perishable goods. The expected lifetime of a cold storage warehouse is 20 to 25 years, and although charge sizes vary widely with system size and design, a rough average is about 4,000 kilograms. Warehouses in developed countries have historically used CFC-12 and R-502 refrigerants and currently use HCFC-22, R-404A, and R-507A. The latter two refrigerants are expected to replace HCFC-22 in new warehouses. Retrofits are also possible; for example, existing CFC-12 cold storage warehouses can be retrofitted with R-401A, and existing R-502 warehouses can be retrofitted with R-402A. Not all cold storage warehouses use halocarbon refrigerants. Many facilities, for example, use ammonia in secondary loop brine systems.

IV.2.1.6 Refrigerated Transport

The refrigerated transport end-use includes refrigerated ship holds, truck trailers, railway freight cars, refrigerated rigid vans/trucks, and other shipping containers. Although charge sizes vary greatly,

the average charge sizes are relatively small (7 to 8 kilograms). The expected lifetime of a refrigerated transport system is 12 years. Trailers, railway cars, and shipping containers using CFC-substitute refrigerants are commonly charged with HFC-134a, R-404A, and HCFC-22 (UNEP, 1999a). Ship holds, on the other hand, rely on HCFC-22 (UNEP, 1999a) and ammonia. In addition to HFC-134a, R-404A can be used in new equipment. Existing equipment can be retrofitted with R-401A, R-402A, R-404A, R-507A, and other refrigerants. In addition, refrigerated transport equipment includes systems that operate based on the evaporation and expansion of liquid CO₂ or nitrogen.

IV.2.1.7 Industrial Process Refrigeration

Industrial process refrigeration includes complex, often custom-designed refrigeration systems used in the chemical, petrochemical, food processing, pharmaceutical, oil and gas, and metallurgical industries; in sports and leisure facilities; and in many other applications. Charge sizes typically range from 650 to 9,100 kilograms, and the average lifetime is approximately 25 years. Ammonia, HCs, HCFC-123, and HFC-134a are expected to be the most widely used substitute refrigerants for new equipment in the near future (UNEP, 1999a). Upon completion of the HCFC phaseout, HFC-134a, R-404A, and R-507A are expected to be the primary refrigerants used in this end-use.

IV.2.1.8 Residential and Small Commercial Air-Conditioning and Heat Pumps

Residential and small commercial air-conditioning (e.g., window units, unitary air conditioners, and packaged terminal air conditioners) and heat pumps are another source of HFC emissions. Most of these units are window and through-the-wall units, ducted central air conditioners, and nonducted split systems. The charge sizes of the equipment in this sector range from 0.5 to 10 kilograms for residential systems, and about 10 to 180 kilograms for commercial systems based on cooling capacity requirements. The average lifetime of this type of equipment is 15 years. Residential and commercial air-conditioning has been relying almost exclusively on HCFC-22 refrigerant. R-410A, R-407C, and HFC-134a are currently used to replace HCFC-22 in some new equipment for most end-uses, and this trend is expected to continue as HCFC-22 is phased out. In particular, R-410A is expected to dominate the U.S. residential market in the future, whereas R-407C is expected to replace HCFC-22 in retrofit applications and some new residential and commercial equipment. Other countries may experience different patterns of R-410A and R-407C use.

IV.2.2 Baseline Emissions Estimates

IV.2.2.1 Emissions Estimating Methodology

Description of Methodology

Specific information on how the model calculates refrigeration and air-conditioning emissions is described below.

The USEPA's Vintaging Model and industry data were used to simulate the aggregate impacts of the ODS phaseout on the use and emissions of various fluorocarbons and their substitutes in the United States. Emissions estimates for non-U.S. countries incorporated estimates of the consumption of ODSs by country, as provided by the United Nations Environment Programme (UNEP, 1999b). The estimates for EU-15 were provided in aggregate, and each country's gross domestic product (GDP) was used as a proxy to divide the consumption of the individual member nations by the EU-15 total. Estimates of country-specific ODS consumption, as reported under the Montreal Protocol, were then used in conjunction with Vintaging Model output for each ODS-consuming sector. In the absence of country-level data, preliminary estimates of emissions were calculated by assuming that the transition from ODSs to

HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in (1) economic growth; (2) rates of ODS phaseout; and (3) the distribution of ODS use across end-uses in each region or country, as explained below.

Emissions Equations

For refrigeration and air-conditioning products, emissions calculations were split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. The first equation calculates the emissions from leakage and service, and the second equation calculates the emissions resulting from disposal of the equipment. These service, leakage, and disposal emissions were added to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, improvements in their leakage, service, and disposal emissions rates were assumed to occur.

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \text{ for } i = 1 \rightarrow k \quad (2.1)$$

where

- Es = Emissions from equipment serviced. Emissions in year j from normal leakage and servicing of equipment.
- l_a = Annual leakage rate. Average annual leakage rate during normal equipment operation, expressed as a percentage of total chemical charge.
- l_s = Service leakage rate. Average annual leakage from equipment servicing, expressed as a percentage of total chemical charge.
- Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment in a given year, by weight.
- j = Year of emissions.
- i = Counter. From 1 to lifetime (k).
- k = Lifetime. The average lifetime of the equipment.

Note: It is recognized that leakage rates are not a function of the total system, but change with system pressure and temperature. For instance, when equipment charges are diminished because of refrigerant losses (i.e., leakage), system pressures are also reduced somewhat and the leakage rate changes. This change becomes appreciable once the entire liquid refrigerant is gone. The average leakage rates used in the equation above were intended to account for this effect. The rates also accounted for the range of equipment types (from those that do not leak at all to those with high leaks) and service practices (i.e., proper refrigerant recovery and refrigerant venting).

Emissions also occur during equipment disposal. The disposal emissions equations assumed that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)] \quad (2.2)$$

where

- Ed = Emissions from equipment disposed. Emissions in year j from the disposal of equipment.
- Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment one lifetime (k) ago, by weight.
- rm = Chemical remaining. Amount of chemical remaining in equipment at the time of disposal, expressed as a percentage of total chemical charge.
- rc = Chemical recovery rate. Amount of chemical that is recovered just prior to disposal, expressed as a percentage of chemical remaining at disposal (rm).
- j = Year of emissions.
- i = Counter. From 1 to lifetime (k).
- k = Lifetime. The average lifetime of the equipment.

Finally, lifetime and disposal emissions were summed to provide an estimate of total emissions:

$$E_j = Es_j + Ed_j \quad (2.3)$$

where

- E = Total emissions. Emissions from refrigeration and air-conditioning equipment in year j.
- Es = Emissions from equipment serviced. Emissions in a given year from normal leakage and servicing (recharging) of equipment.
- Ed = Emissions from equipment disposed. Emissions in a given year from the disposal of equipment.
- j = Year of emissions.

Regional Variations and Adjustments

From the general methodology, the following regional assumptions were applied:

- **Adjustment for Regulation (EC) No 2037/2000.** Countries in the EU-15 were assumed to be in full compliance with Regulation (EC) No 2037/2000, which stipulates that no new refrigeration and air-conditioning equipment should be manufactured with HCFCs, as of January 1, 2002.² The European Commission (EC) regulation also bans the use of HCFCs for servicing equipment after January 1, 2015. Compliance with these regulations will likely lead to increased use of HFCs to replace HCFCs. These changes were assumed to correspond to increased emissions of 20 percent in 2005, 15 percent in 2010, and 15 percent in 2020, relative to what the EU-15 baseline otherwise would be. These relative emissions increases were determined by running a Vintaging Model scenario where the uses of HCFCs were assumed to comply with the regulation. No adjustments for Regulation (EC) No 2037/2000 were made to the 10 countries that joined the EU in March 2004, as this analysis was conducted prior to this date.

² The ban was delayed until July 1, 2002, for fixed air-conditioning equipment with a cooling capacity of less than 100 kW and until January 1, 2004, for reversible air-conditioning/heat pump systems.

- **Recovery and Recycling Adjustments.** For developing (i.e., non-Annex I) countries, countries with economies in transition (CEITs), and Turkey, the emissions were increased by approximately 20 percent over initial estimates to reflect the assumed low levels of recovery and recycling of refrigerants from small end-uses (i.e., MVACs, commercial and residential air-conditioning, refrigerated transport, and other appliances), relative to the United States. This assumed increase in emissions from lower levels of recovery and recycling was based on an analysis of a variety of scenarios using the Vintaging Model, where emissions were first projected assuming an 80-percent baseline recovery rate to reflect the assumed status quo in developed countries and then projected again assuming a 30-percent baseline recovery rate to reflect the assumed status quo in developing countries. The GWP-weighted emissions in the latter low-recovery scenario were determined to be approximately 20 percent higher than in the former high-recovery scenario (ICF Consulting, 2002a).
- **Market Adjustments.** The baseline assumes that HC and ammonia refrigerants and other non-HFC or low-emitting options will penetrate international markets more than the United States market because of differences in safety standards; greater acceptance of non-HFC choices by industry, end-users, regulators, and insurance companies; and increased public and regulatory scrutiny to reduce HFC emissions. To reflect this penetration, baseline emissions estimates of non-U.S. countries were reduced by the following amounts (Table 2-1).

Table 2-1: Reductions in Baseline Emissions in Non-U.S. Countries to Reflect Market Adjustments

Country/Region	Percent
EU-15	30 ^a
Japan	30
Non-EU-15 Europe	20 ^a
CEITs	20
Australia/New Zealand	10
All other countries	20

EU-15 = European Union; CEITs = countries with economies in transition.

^a The new EC Directive on MVACs, which bans the use of HFC-134a in new vehicle models in 2011 and in all vehicles in 2017, was not considered in developing these baseline emissions adjustments for EU countries, as the directive was not finalized at the time this analysis was conducted.

These assumptions were based solely on qualitative information on current and future global market penetration of low-GWP refrigerants, as well as low-emission technologies and practices. For example, HC technology is believed to dominate the domestic refrigeration market in Western Europe, particularly in Germany and Scandinavia. HC domestic refrigerators are produced by major manufacturers in Germany, Denmark, Italy, Japan, United Kingdom, France, Spain, and Sweden. Some of the largest manufacturers in China, India, Indonesia, Australia, Korea, and Cuba are also producing domestic refrigerators that use HCs (Greenpeace, 2001; Japan Times, 2002). To reflect this and many other trends, baseline emissions from non-U.S. countries were adjusted downward, as shown above.

- **Redistribution of Emissions by End-Use, Based on MVAC Analysis.** Based on a variety of available data on international motor vehicle sales, air-conditioning usage, and MVAC emissions, a separate analysis was conducted to estimate total MVAC emissions by region. These MVAC emissions estimates by region were then used to determine the relative share of refrigeration and air-conditioning emissions attributable to MVACs and to reapportion emissions from all other end-uses accordingly, relative to the end-use breakout calculated for the United States. The methodology used to perform this analysis is explained in detail below.

MVAC Analysis

The Vintaging Model estimates MVAC emissions for the United States based on vehicle sales data, assumptions on the percentage of vehicles with functional air-conditioning, and a projected growth rate of 2.6 percent (based on sales data from 1970 through 2001). Table 2-2 presents the Vintaging Model's estimated percentage of baseline refrigeration and air-conditioning emissions attributable to MVACs in the United States from 2005 through 2020.

Table 2-2: Estimated Percentage of GWP-Weighted Refrigeration and Air-Conditioning HFC Emissions Attributable to MVACs in the United States

	2005	2010	2015	2020
Percent	35.9	27.6	22.6	19.9

However, because the market penetration of air-conditioning into vehicles is assumed to be different in other countries and regions,³ and because MVACs are assumed to account for a different proportion of total refrigeration and air-conditioning emissions in the United States compared with most other developed and developing countries, this end-use has been modeled separately to achieve a higher degree of accuracy in emissions estimates. To this end, for all countries for which data on MVACs or historical vehicle sales were available, country-specific MVAC models were developed to estimate the total number of MVACs in past, present, and future years. Ward's World Motor Vehicle Data (2001), the Society of Indian Automobile Manufacturers (SIAM) (2005), and the China Association of Automobile Manufacturers (2005) were used as data sources.

The remainder of this section describes the assumptions and data used to project the number of MVACs by country and region. It should be noted that, while the MVAC industry is investigating new refrigerants and other emissions reduction initiatives (see <http://www.epa.gov/cppd/mac/>), these actions are not considered in the baseline estimates.

India

India's MVAC fleet estimates were developed based on (1) data on MVAC sales prior to 2004, from SIAM (2005), (2) projected annual growth rates of new vehicle sales, and (3) projected annual growth rates of air-conditioning penetration. Specifically, India's future vehicle fleet growth was assumed to be 8 percent per year,⁴ while air-conditioning penetration was assumed to increase linearly to reach 95 percent in 2010.⁵ Beyond 2010, it was assumed that air-conditioning penetration will be maintained at 95 percent because vehicle air-conditioning will become standard. The assumed air-conditioning market penetration rates for India are summarized in Table 2-3.

Table 2-3: Percentage of Newly Manufactured Vehicles Assumed to Have Operational Air-Conditioning Units in India

	2005	2010	2015	2020
Percent	92.5	95	95	95

³ Except for Japan, which is assumed to have the same market penetration rate of MVACs into new vehicles as the United States.

⁴ This growth rate was based on the annual growth rate of passenger vehicles (assumed to be linear) between 2000 and 2004, with the fleet size in 2000 based on Ward's (2001) and the fleet size in 2004 based on SIAM (2005).

⁵ Air-conditioning penetration was grown from 92 percent in 2004, based on data from SIAM (2005).

China

MVAC estimates for China are based on data on Chinese production of vehicles with air-conditioning from 1994 to 2004, provided by the China Association of Automobile Manufacturers (2005). Projections of future MVACs in China were based on the assumed growth rate of India's vehicle market beyond 2005 (assumed to be 8 percent per year, as described above).⁶ The same assumptions were applied to Hong Kong.

All Other Countries

For all countries other than the United States, Japan, India, China, and Hong Kong, the number of operational MVACs was estimated based on (1) annual historical sales of passenger cars and light trucks, as provided in Ward's (2001), and (2) estimates of the percentage of the vehicle fleet equipped with air-conditioning, based on quantitative and qualitative data provided in EC (2003); Hill and Atkinson (2003); OPROZ (2001); and Barbusse, Clodic, and Roumegoux (1998), as presented in Table 2-4.

Table 2-4: Percentage of Newly Manufactured Vehicles Assumed to Have Operational Air-Conditioning Units in All Other Countries

Country/Region	2005	2010	2015	2020
All other Annex I countries	65.5	70.0	80.5	95.0
Latin America and Caribbean	50.0	55.0	60.0	65.0
All other non-Annex I countries, Russian Federation, and Ukraine	23.0	28.0	33.0	38.0

As shown above, MVACs were assumed to increasingly penetrate the vehicle fleet over time. In the developing countries that were modeled, this rate of increase was assumed to be 1 percent each year, while in all other Annex I countries, the rate of increase was assumed to be more rapid, reaching 95 percent of the vehicle fleet in 2020 (EC, 2003; Hill and Atkinson, 2003).

Once the MVAC fleet was estimated by country/region, annual MVAC emissions were calculated assuming annual average leak and service emissions of 10.9 percent.⁷ MVAC emissions at disposal were assumed to be 42.5 percent of the original MVAC charge in developed countries and 69 percent in developing countries (as a result of zero recovery assumed).⁸ All systems were assumed to use HFC-134a refrigerant in the baseline. The new EC Directive on MVACs⁹ was not considered in the baseline estimates, as this directive was not finalized at the time this analysis was conducted.

⁶ India's projected growth rate was selected for use in place of China's historical growth rate because China's historical growth rate (of approximately 25%) was considered unrealistically high to maintain for 2.5 decades.

⁷ This emissions rate includes emissions released during routine equipment operation from leaks, as well as those released during the servicing of equipment by both professionals and do-it-yourselfers.

⁸ This percentage (69 percent) is the implied loss at disposal given the assumption that twice the original MVAC charge is emitted over the course of a vehicle's lifetime in developing countries.

⁹ In April 2006, the European Parliament adopted a legislative resolution on the joint text approved by the Conciliation Committee for a directive of the European Parliament and of the Council relating to emissions from air conditioning systems in motor vehicles and amending Council Directive 70/156/EEC. The directive places a ban on the use of fluorinated gases with a GWP of more than 150 in new vehicle models planned from 2011 onwards, and in all vehicles from 2017 onwards.

Once MVAC emissions were estimated by country/region, the proportion of MVAC emissions as a percentage of the total refrigeration and air-conditioning emissions (developed using the methodology described above) was calculated. These percentages were then averaged by region. The average estimated percentage of refrigeration and air-conditioning GWP-weighted emissions that are attributable to MVACs by regional grouping are presented in Table 2-5.

Table 2-5: Estimated Percentage of Refrigeration and Air-Conditioning HFC Emissions Attributable to MVACs

Country/Region	2005	2010	2015	2020
United States and Japan	35.9	27.6	22.6	19.9
All other Annex I countries	46.9	42.8	31.8	36.6
China, Hong Kong, and India	41.3	53.0	62.0	65.8
Latin America and Caribbean	14.2	13.3	12.6	12.0
Russian Federation, Ukraine, and all other non-Annex I countries	3.8	3.8	5.4	8.0

Based on the above percentage of sector baseline emissions assumed to come from MVACs for each region, for lack of reliable data to suggest otherwise, the U.S. baseline emissions breakout by end-use was used to proportionally redistribute the remaining emissions of a particular country/region. For example, because MVACs contributed only 14.2 percent of total sector emissions in Latin American countries in 2005, the balance of emissions in Latin America was distributed across all other end-uses, in proportion to the U.S. end-use breakout. The resulting subdivision of baseline GWP-weighted HFC emissions by end-use and region are summarized in Table 2-6. These emissions subdivisions by end-use help determine the maximum amount of emissions that can be avoided by any given abatement option, because each option is applicable only to specific end-uses.

IV.2.2.2 Baseline Emissions

The amount of HFC emissions from MVAC units is expected to rise, because HFC-134a has been the primary refrigerant used in the growing automobile industry, and because HFC-134a is the primary refrigerant used to replace older CFC-12 systems. The baseline for MVACs assumes a mix of professionally serviced systems and those serviced by people without recovery equipment. Because commercial unitary and residential air-conditioning equipment has yet to transition fully into HFCs, the emissions of HFCs from these end-uses in 2005 were estimated to be relatively insignificant, but will increase substantially over time. Retail food systems are expected to (and in many cases, already have) transition at least partially to HFC-134a and HFC-containing blends because of certain equipment characteristics (such as their large number of fittings); such systems may have higher refrigerant emissions rates. Cold storage systems also have large charge sizes, but their emissions relative to other refrigeration and air-conditioning end-uses are not expected to increase significantly. HFC emissions from chillers are relatively low as a result of the continued use of HCFC-123 in this application,¹⁰ as well as the low leakage rates of new HFC-134a units. The baseline emissions projections assumed that the recovery and recycling of refrigerants during service and disposal in Annex I countries will curtail emissions across all end-uses.

¹⁰ Note that emissions of all CFC and HCFC refrigerants, including HCFC-123, were not included in the baseline emissions estimates.

The resulting baseline estimates of HFC emissions are summarized in Table 2-7 and Figure 2-1 in million metric tons of carbon dioxide equivalents (MtCO₂eq).

IV.2.3 Cost of HFC Emissions Reduction from Refrigeration and Air-Conditioning

This section presents a cost analysis for achieving HFC emissions reductions from the emissions baselines presented above. Each abatement option is described below, but only those options not assumed to occur in the baseline and for which adequate cost data are available were included in the cost analysis. To the extent possible, this analysis considered total equivalent warming impacts (TEWI)¹¹ to account for the climate and cost impacts of energy consumption (i.e., indirect emissions). Because of data limitations, a full life cycle analysis was not possible. For example, the cost and emissions impacts associated with (1) the manufacture of refrigerant and all system components, (2) the energy required for reclamation, and (3) the recycling of all system components at the end of equipment life were not assessed in this analysis.

The remainder of this section describes the economic assumptions for these abatement options.

IV.2.3.1 Description and Cost Analysis of Abatement Options

HFC emissions from refrigeration and air-conditioning equipment can be reduced through a variety of practice and technology options. Many of the options considered in this report would require voluntary action by the private sector or further government regulation. For example, national governments can regulate maximum allowable leakage rates for refrigeration and air-conditioning equipment and/or require the recovery of refrigerant and the proper disposal of nonreclaimable refrigerant. Many Annex I countries have already implemented a variety of such regulatory actions to reduce ODS emissions. Some of the most widely recognized options to reduce refrigerant emissions are listed below (UNEP, 1998; UNEP, 1999a; Crawford, 1999; USEPA, 2001a).

Practice Options

- leak repair
- refrigerant recovery and recycling
- proper refrigerant disposal
- technician certification and HFC sales restriction

Alternative Refrigerant Options

- ammonia
- HCs
- CO₂
- other low-GWP refrigerants

¹¹ TEWI is the combined effects of *direct* greenhouse gas impacts (i.e., chemical emissions) and *indirect* greenhouse gas impacts (i.e., energy-related CO₂ emissions).

Table 2-6: Distribution of Refrigeration- and Air-Conditioning–Sector HFC Emissions by End-Use, Region, and Year (Percent)

End-Use	United States and Japan	All Other Annex I Countries	Latin America and Caribbean	China, Hong Kong, and India	All Other Non-Annex I Countries, Russian Federation, and Ukraine
2005					
Chillers	3.2	2.7	4.3	3.0	4.8
Retail food	39.0	32.3	52.2	35.7	58.4
Cold storage	1.2	1.0	1.6	1.1	1.8
Industrial process	4.6	3.8	6.1	4.2	6.8
Commercial air-conditioning	1.1	0.9	1.4	1.0	1.6
Residential air-conditioning	0.6	0.5	0.8	0.6	0.9
Refrigerated transport	14.0	11.6	18.8	12.8	21.0
Other appliances ^a	0.5	0.4	0.6	0.4	0.7
MVACs	35.9	46.9	14.2	41.3	3.8
2010					
Chillers	2.3	1.8	2.8	1.5	3.1
Retail food	41.7	33.0	50.0	27.0	55.4
Cold storage	1.4	1.1	1.7	0.9	1.9
Industrial process	6.0	4.8	7.2	3.9	8.0
Commercial air-conditioning	5.3	4.2	6.3	4.3	7.0
Residential air-conditioning	5.5	4.4	6.6	3.6	7.4
Refrigerated transport	9.7	7.7	11.6	6.3	12.9
Other appliances ^a	0.4	0.3	0.5	0.3	0.6
MVACs	27.6	42.8	13.3	53.2	3.8
2015					
Chillers	1.8	1.6	2.0	0.9	2.2
Retail food	41.2	36.3	46.5	20.2	50.3
Cold storage	1.4	1.2	1.6	0.7	1.7
Industrial process	6.4	5.6	7.2	3.1	7.8
Commercial air-conditioning	8.8	7.8	10.0	4.3	10.8
Residential air-conditioning	9.7	8.5	10.9	4.7	11.8
Refrigerated transport	7.2	6.3	8.1	3.5	8.7
Other appliances ^a	1.0	0.9	1.1	0.5	1.2
MVACs	22.6	31.8	12.6	62.0	5.4
2020					
Chillers	1.5	1.2	1.6	0.6	1.7
Retail food	39.1	31.0	43.0	16.7	44.9
Cold storage	1.4	1.1	1.6	0.6	1.6
Industrial process	6.6	5.2	7.3	2.8	7.6
Commercial air-conditioning	11.3	8.9	12.4	4.8	12.9
Residential air-conditioning	13.3	10.5	14.6	5.7	15.2
Refrigerated transport	6.1	4.9	6.7	2.6	7.0
Other appliances ^a	0.8	0.6	0.9	0.3	0.9
MVACs	19.9	36.6	12.0	65.8	8.0

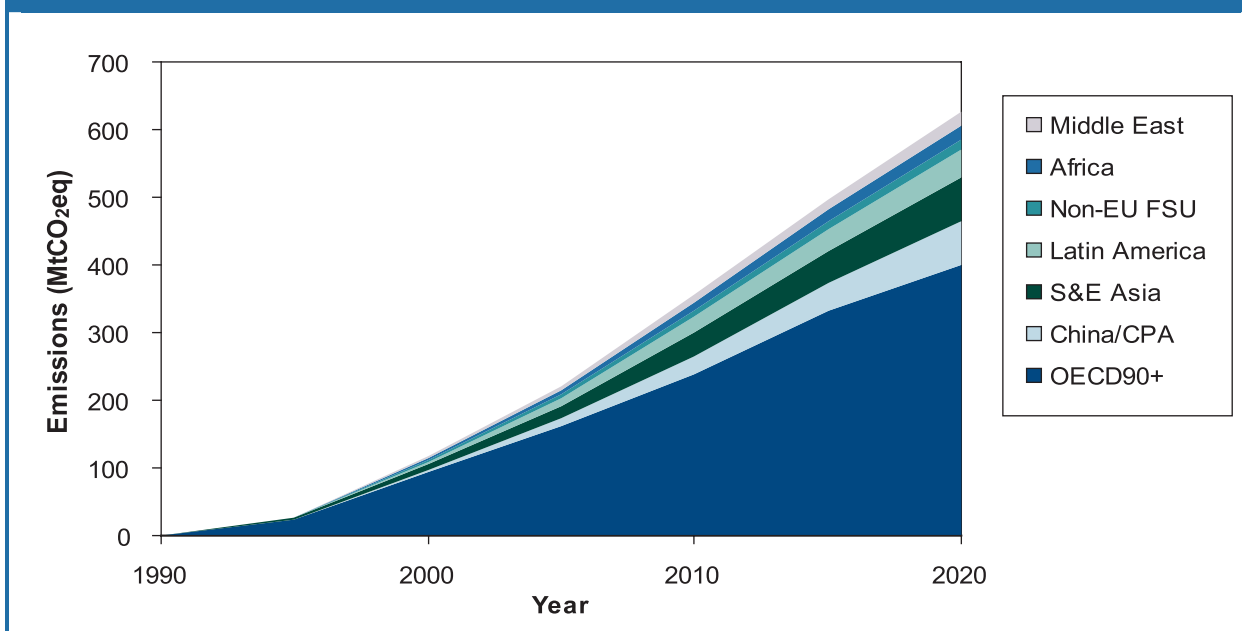
Note: Totals may not sum because of independent rounding.

^a Other appliances include refrigerated appliances, dehumidifiers, and ice makers.

Table 2-7: Total Baseline HFC Emissions from Refrigeration and Air-Conditioning (MtCO₂eq)

Region	2000	2010	2020
Africa	2.8	12.8	20.4
Annex I	95.1	244.9	414.4
Australia/New Zealand	1.3	3.2	5.6
Brazil	1.5	6.9	12.0
China	4.1	25.8	61.7
Eastern Europe	0.9	4.2	7.3
EU-15	13.3	37.9	58.4
India	0.5	2.6	5.4
Japan	16.4	32.6	45.1
Mexico	1.4	6.6	11.2
Non-OECD Annex I	1.8	9.3	17.3
OECD	98.5	260.8	441.4
Russian Federation	1.3	6.9	13.4
South & SE Asia	2.9	14.7	28.1
United States	58.0	148.6	264.6
World Total	117.0	356.4	627.3

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 2-1: Baseline HFC Emissions from Refrigeration and Air-Conditioning by Region (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development.

Technology Options

- distributed systems¹² for stationary commercial refrigeration equipment
- secondary loop systems for stationary equipment, including HFC secondary loop systems and ammonia secondary loop systems
- enhanced HFC-134a systems in MVACs
- HFC-152a refrigerant in MVACs (direct expansion or secondary loop systems)
- CO₂ systems in MVACs
- oil-free compressors
- geothermal (in lieu of air-to-air) cooling systems
- desiccant cooling systems
- absorption systems

Table 2-8 summarizes the duration and applicability of the process and technology emissions reduction options across all end-use applications considered in this analysis. The applicability of the alternative refrigerant options depends on the technology used; hence, some options were explored in more detail in the analysis of technology options. Consideration of distribution costs associated with the technology options was not included in the analysis. All costs are presented in 2000 dollars.

The following section describes all of these options in greater detail and presents a cost analysis for those options not assumed to occur in the baseline and for which adequate cost data were available. The resulting emissions abatement potentials and costs of each option explored in the cost analysis are summarized in Section IV.2.4. The technology options explored in this chapter do not include retrofit costs and, therefore, were assumed to penetrate only the markets of new (not existing) equipment. New equipment is defined as air-conditioning and refrigeration equipment manufactured in 2005 or later. Detailed descriptions of the cost and emissions reduction analysis for each option can be found in Appendix F for this chapter.

¹² The term distributed system, as used in this report, refers to commercial refrigeration equipment used in retail food and cold storage applications, although the term could also refer to equipment used in other applications, such as residential and small commercial air-conditioning.

Table 2-8: Assumptions on Duration and Applicability of Emissions Reduction Options

Option Description	Duration of Emissions Reduction (Years)	Potential Applicability to End-Use Equipment									
		Chillers	Retail Food	Cold Storage Warehouses	Refrigerated Transport	Industrial Process Refrigeration	Commercial Air-Conditioning			Household Refrigeration and Small Appliances	
							MVACs	Residential Air-Conditioning			
Practice Options											
Leak repair	5	✓	✓	✓	■	✓	■	■	■	■	■
Refrigerant recovery	1	■	■	■	✓	■	✓	■	✓	■	✓
Proper refrigerant disposal	NA	■	■	■	■	■	■	■	■	■	■
Technician certification	NA	■	■	■	■	■	■	■	■	■	■
Alternative Refrigerants											
Ammonia	Lifetime of equipment	■	✓	✓	■						■
HCs	Lifetime of equipment	■	■	■	■	■	■	■	■	■	■
CO ₂	Lifetime of equipment	■	■	■	■	■	■	✓	■	■	■
Other low-GWP refrigerants	Lifetime of equipment	■	■	■	■	■		✓	■	■	■
Technology Options											
Distributed systems for stationary commercial refrigeration equipment	Lifetime of equipment		✓	✓							
Secondary loop systems for stationary equipment—HFC primary refrigerant	Lifetime of equipment		✓	✓		■					
Secondary loops systems for stationary equipment—ammonia primary refrigerant	Lifetime of equipment		✓	✓		■					
Enhanced HFC-134a systems in MVACs	Lifetime of equipment							✓			
HFC-152a in MVACs (direct expansion or secondary loop)	Lifetime of equipment							✓			
CO ₂ in MVACs	Lifetime of equipment							✓			
Oil-free compressors	Lifetime of equipment								■	■	■
Geothermal (in lieu of air-to-air) cooling systems	Lifetime of equipment	■	■	■	■	■					
Desiccant cooling systems	Lifetime of equipment	■							■	■	
Absorption systems	Lifetime of equipment	■							■	■	

NA: Not applicable.

✓ Option is technically feasible and was addressed in the cost analysis of this report.

■ Option is potentially feasible but was not addressed in the cost analysis of this report, either because it is current practice (assumed to occur in the baseline) or because insufficient information was available to include it in the cost analysis.

Practice Options

Four practice options are discussed in this section—leak repair, refrigerant recovery, proper refrigerant disposal, and technician certification. Together with additional measures (including designing and installing equipment to minimize HFC emissions), these practices are often considered standard good practices and are identified in a number of different responsible use guides—such as that published by the Alliance for Responsible Atmospheric Policy (ARAP) (see <http://www.arap.org/responsible.html>)—and endorsed through voluntary industry partnerships, including those initiated by the USEPA (see <http://www.epa.gov/ozone/snap/emissions/index.html>). However, this report assumes that there are opportunities to further apply these options to reduce emissions from the baseline prepared for this report.

Leak Repair for Large Equipment

Reducing leakage rates can significantly reduce HFC emissions, especially in systems such as chillers, cold storage warehouses, and retail food systems that can leak large amounts of refrigerant. Although some of the options available may be impractical for existing equipment, given the difficulty and expense of retrofitting, there are still many options that are economically feasible. Some of the leak repair options used in current industry practice include

- use of preventive maintenance, including scheduled inspection and repairs;
- monitoring of leaks using stationary leak monitors or other new technologies, such as early warning signals,¹³ remote monitoring, and diagnostics;
- use of new, more durable gasket materials that provide tighter seals and absorb less refrigerant;
- augmentation of threaded joints with O-ring seals;
- augmentation or replacement of gaskets and O-rings with adhesive sealants;
- broader use and improvement of brazing techniques rather than threaded or snap fittings (e.g., use of sufficient silver content¹⁴ and use of dry nitrogen or other inert gas to avoid oxidation);
- focus on ensuring accessibility to field joints and use of isolation valves, which allows for greater ease of repair;
- focus on proper securing to reduce vibration fractures in the pipe and connections from the compressor and other moving parts of the system;
- repair or retrofit of high-emitting systems through targeted component upgrades;¹⁵ and
- performance of major modifications to the systems (USEPA, 1997; USEPA, 1998; Calm, 1999).¹⁶

¹³ Technologies in the final stages of development are expected to generate early warning signals at less than 5 percent charge loss in commercial refrigeration and air-conditioning systems (Gaslok, 2002).

¹⁴ For solder, a 15-percent silver content is recommended (USEPA, 1997).

¹⁵ This option may include replacing the purge unit or other component upgrades that typically require the removal of refrigerant from the machine, 2 full days of two technicians' time, and several thousand dollars' worth of materials (USEPA, 1998).

As suggested by the above list, leak reduction options range from simple repairs to major system upgrades. Even in countries where maximum allowable leakage rates are regulated by law, further leak reduction improvements, such as the replacement or upgrade of a major system component, are still possible. For example, preliminary data gathered from U.S. industry indicate that leakage rates for certain types of existing equipment in the United States range from 8 to 40 percent, whereas achievable leakage rates for new or modified equipment range from 4 to 15 percent. According to the Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP), studies have reported global annual refrigerant loss from supermarket refrigeration systems to range from 3.2 percent in the Netherlands to 22 percent in the United States (IPCC/TEAP, 2005). For this same type of equipment, the International Energy Agency (IEA) estimates that historical leakage rates have been 30 percent or higher, whereas newer systems can achieve leakage rates of approximately 15 percent or slightly lower (IEA, 2003). Some newer retail food equipment has reached leakage rates of less than 10 percent (Crawford, 2002).

Since the lower-cost leak reduction options represent significant cost savings, this analysis assumes that the leak reductions occur under the baseline. The cost analysis therefore focused only on the more extensive and costly options. This option was assumed to be technically applicable¹⁷ to all equipment with large charge sizes (i.e., chillers, retail food refrigeration, cold storage, and industrial process refrigeration). This analysis assumed that 50 percent of emissions occur as a result of equipment leakage during routine operation, while the other 50 percent of emissions are released during equipment servicing and disposal. Thus, the maximum technical applicability of this option was assumed to be 50 percent of emissions from large equipment (see Table 2-9). Furthermore, this analysis assumed that leak repair can reduce annual system leakage by 40 percent, using an example of a supermarket system that leaks at 25 percent annually but only at 15 percent following repairs. The project lifetime was assumed to be 1 year. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-9. Assumptions on maximum market penetration for each region and year are presented in Table 2-19.

Refrigerant Recovery and Recycling from Small Equipment

Recovery and recycling of HFCs help to decrease HFC emissions during equipment service and disposal. The approach involves the use of a refrigerant recovery device that transfers refrigerant into an external storage container prior to servicing of the equipment. Once the recovery process and source operations are complete, the refrigerant contained in the storage container may be recharged back into the equipment, cleaned through the use of recycling devices, sent to a reclamation facility to be purified,¹⁸ or disposed of through the use of incineration technologies. Refrigerant recovery may also be an

¹⁶ This option may include modifications that are not strictly leak repair, but would result in greatly reduced leakage rates. For example, combining the installation of a new purge system, the replacement of flare joints, and other containment options, or combining the replacement of gaskets and seals, replacement of the motor, and installation of new refrigerant metering.

¹⁷ In this report, the terms “technically applicable” and “technical applicability” refer to the emissions to which an option can theoretically be applied. The leak repair option was assumed to be technically applicable to all emissions from leaks (but not servicing and disposal) from the four end-uses listed in Table 2-9.

¹⁸ Recycling cleans and reclamation purifies recovered refrigerant; reclamation is more thorough and involves repeated precision distillation, filtering, and contaminant removal. Recycling is used for on-site servicing of MVACs and other equipment, and reclamation requires sending the refrigerant off-site to a reclaimer.

Table 2-9: Summary of Assumptions for Leak Repair for Large Equipment

Country/Region	Applicable End-Uses ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	Chillers Retail food Cold storage Industrial process	40.0%	25.7%	24.3%
Other Annex I countries			20.3%	19.3%
Latin America and Caribbean			30.8%	26.7%
China, Hong Kong, and India			16.7%	10.4%
Other non-Annex I countries, Russian Federation, and Ukraine			34.2%	27.9%

^a End-uses and reduction efficiency apply to all regions.

^b Technical applicability is shown as a percentage of total refrigeration- and air-conditioning-sector emissions and equals 50 percent of total refrigeration and air-conditioning emissions from chillers, retail food refrigeration, cold storage, and industrial process refrigeration. See Section IV.2.4 for a more complete explanation of how technical applicability, reduction efficiency, and market penetration were used to calculate emissions reductions associated with each option.

important way to reduce emissions from near-empty refrigerant containers (i.e., can heels). Refrigerant recovery is assumed to be widely practiced in Annex I countries in the baseline, where the procedure is typically required by law.

This analysis assesses only the recovery of refrigerant from small equipment (i.e., MVACs, refrigerated transport, household and other small appliances, and unitary equipment) above that which is already practiced (e.g., recovery due to regulations in many developed countries or for economic reasons) at service and disposal. It is assumed that recovery from large equipment is already widely practiced in the baseline¹⁹ because of the significant cost savings associated with recovery of large quantities of refrigerant from this equipment. Because emissions reductions and costs vary by scenario and end-use, emissions reductions and costs associated with four recovery scenarios were averaged to obtain one breakeven cost. The four scenarios studied were recovery and recycling of refrigerant from (1) MVACs at service, (2) MVACs at disposal, (3) small appliances at service, and (4) small appliances at disposal.

This analysis assumed that 50 percent of emissions are released during equipment servicing and disposal, while the remaining 50 percent occur as a result of leakage during normal operations. Thus, the technical applicability²⁰ of this option is 50 percent of emissions from small equipment (see Table 2-10). Furthermore, because in the United States small appliances are considered completely recovered when 90 percent of the refrigerant is removed from units with running compressors, or when 80 percent of the refrigerant is removed from units with nonoperating compressors, this analysis assumed that the reduction efficiency of this option is 85 percent (Contracting Business Interactive, 2003; USEPA, 1993). The project lifetime is assumed to be 1 year. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-10. Recovery from small appliances and MVACs was

¹⁹ Although the Society of Automotive Engineers (SAE) has issued industry standards on equipment and technician procedures that apply to MVACs and provide for on-site recovery and recycling of HFC-134a from MVAC systems for reuse in the serviced system, recovery from these and other small systems is still not believed to be widely practiced in most developing countries as a result of a lack of infrastructure (i.e., recovery and recycling equipment) (World Bank, 2002).

²⁰ In this report, the terms “technically applicable” and “technical applicability” refer to the emissions to which an option can theoretically be applied. The refrigerant recovery and recycling option was assumed to be technically applicable to all emissions during servicing and disposal (but not leaks) from the five end-uses listed in Table 2-10.

Table 2-10: Summary of Assumptions for Recovery and Recycling from Small Equipment

Country/Region	Applicable End-Uses ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	MVAC Refrigerated transport Household and other small appliances Commercial unitary air-conditioning Residential air-conditioning	85.0%	24.3%	25.7%
Other Annex I countries			29.7%	30.7%
Latin America and Caribbean			19.2%	23.3%
China, Hong Kong, and India			33.3%	39.6%
Other non-Annex I countries, Russian Federation, and Ukraine			15.8%	22.1%

^a End-uses and reduction efficiency apply to all regions.

^b Technical applicability is shown as a percentage of total refrigeration- and air-conditioning-sector emissions and equals 50 percent of total refrigeration and air-conditioning emissions from MVACs, refrigerated transport, household and other small appliances, and commercial unitary and residential air-conditioning.

assumed to be practiced at 80 percent in the baseline in developed countries and at 30 percent in the baseline in developing countries. Assumptions on maximum market penetration for each region and year are presented in Table 2-19.

Proper Refrigerant Disposal

One potential source of emissions from the refrigeration and air-conditioning sector is the accidental or deliberate venting of refrigerant. The venting of refrigerant can be reduced by increasing the reclamation of used refrigerant (discussed in more detail below) and properly disposing of refrigerant that cannot be reclaimed (such as highly contaminated refrigerant or mixed refrigerant). Disposal costs vary by country and region, as do transportation costs, storage costs, and access to refrigerant disposal facilities (e.g., high-temperature incinerators that handle refrigerants). Global average ODS destruction costs are estimated to vary between \$1.70 and \$2.60 per pound (approximately \$4 to \$6 per kilogram) (ICF Consulting, 2002b). This option was not explored in the cost analysis as a result of the uncertainty associated with access to disposal facilities and cost disparities within regions.

Technician Certification and HFC Sales Restriction

By ensuring that refrigeration and air-conditioning technicians receive training in proper refrigerant handling, including recovery and recycling practices, or by restricting the sale of HFC refrigerants to certified technicians only, refrigerant emissions can be reduced. In some countries, including the United States, technicians must be certified in accordance with national regulations to purchase CFC and HCFC refrigerants and service refrigeration and air-conditioning equipment. Restricting the use of HFC refrigerants to certified technicians would similarly reduce emissions. To the extent that technician certification and HFC sales restrictions are practiced today, these actions were included in the baseline; additional implementation of these practices was not explored in this analysis due to uncertainty in cost and emissions reductions.

Alternative Refrigerant Options

This section describes four alternative refrigerants: ammonia, hydrocarbons, carbon dioxide, and other low-GWP refrigerants.

Ammonia

Ammonia, primarily used in water-cooled chillers, has excellent thermodynamic properties and can be used in many types of systems. Because ammonia has a strong odor, refrigerant leaks are easier to detect, and because ammonia is lighter than air, dispersion is facilitated in the event of a release (UNEP, 1999a). However, ammonia must be used carefully because it is toxic and slightly flammable. Ammonia is an explosion hazard at 16 to 25 percent in air, which creates a problem in confined spaces. Chillers that use ammonia as a refrigerant are commercially available in Europe and elsewhere, and they have efficiencies that are comparable to those of HFC-134a chillers in some instances. Building and fire codes, however, restrict the use of ammonia in urban areas of the United States and in many other countries. These safety concerns and institutional barriers effectively limit the potential for expanded use of ammonia chillers (Sand, Fischer, and Baxter, 1997).

Whereas the use of ammonia within public spaces, such as supermarkets, is limited in some countries by building codes and ordinances, ammonia is a potential alternative for supermarkets if safety concerns can be adequately addressed through engineering design such as secondary loops and isolation. Indeed, modern ammonia systems manufactured in the United States are fully contained, closed-loop systems with fully integrated controls that regulate pressures throughout the system. Also, all systems are required to have an emergency diffusion system and a series of safety relief valves to protect the system and its pressure vessels from overpressurization and possible failure (ASHRAE, 2002). Systems with ammonia are being built and used in Europe (Sand et al, 1997). However, the further use of ammonia as a supermarket primary refrigerant may be unlikely in the near future in the United Kingdom and other countries because of the capital costs and issues of compliance with standards and safety regulations (Cooper, 1997). Ammonia would also be an option in some industrial process refrigeration and cold storage applications, contingent upon addressing all of the relevant concerns regarding flammability and toxicity. For example, ammonia is used in about 80 percent of current installations of large-size refrigeration plants, as well as in many indirect commercial refrigeration systems (RTOC, 2003).

The chemical properties of ammonia make it incompatible with current designs of light residential and commercial unitary air-conditioning systems, which use copper for the refrigerant tubing, in the heat exchangers, and in other components. In the presence of water, ammonia cannot be used with copper or zinc (UNEP, 1999a); however, ammonia can be used in aluminum and steel systems. Compatible components would need to be developed to use ammonia. As a result of these technical and cost barriers, as well as ammonia's flammability and toxicity, ammonia is considered an unlikely candidate for use in commercial and residential unitary equipment (Sand et al., 1997).

Many of the existing uses of ammonia were included in the baseline analysis. One additional option—using ammonia secondary loop systems in retail food and cold storage end-uses—is analyzed in more detail in the section on “Technology Options” that follows this section on alternative refrigerant options.

HCs

HCs have thermodynamic properties comparable to fluorocarbons that make them good refrigerants; however, the high flammability of HCs causes safety concerns. Considering technical requirements alone, there is potential for use of HCs in retail food refrigeration, refrigerated transport, household refrigeration, residential air-conditioning, MVACs, and commercial unitary systems. Currently used refrigerants include HC-600a, HC-290, and HC-1270 (UNEP, 1999a). In addition to good thermodynamic properties, HCs have other advantages such as energy efficiencies comparable to fluorocarbons, zero ozone depletion potential (ODP), and very low direct GWP.

The primary disadvantage of HCs is their flammability, resulting in significant safety and liability issues. These concerns cause increased costs for safety precautions in factories and can necessitate design changes in every application, such as relocation of electrical components to reduce the likelihood of accidents from potential leaks (Kruse, 1996; Paul, 1996). These concerns also entail additional hardware costs for many applications (ADL, 1999; Crawford, 2000). HC refrigerant use is generally restricted by U.S. safety codes, and with the exception of industrial refrigeration, the USEPA has not listed HCs as acceptable substitutes to ODS refrigerants (per Section 612 of the Clean Air Act Amendments of 1990). Even if systems that are designed to use HC refrigerants were listed, liability concerns would remain. Systems using flammable refrigerants will require additional engineering and testing, development of standards and service procedures, and training of manufacturing and service technicians before commercialization.

HC domestic refrigerators have been available in Western Europe since the early 1990s, and have now fully penetrated some of the new domestic refrigeration markets. HC domestic refrigerators are available in Argentina, Australia, Brazil, China, Cuba, Germany, India, Indonesia, Japan, and elsewhere. Similarly, HC refrigerants are available in other products, although little information is readily available regarding their market success to date (Hydro Cool Online, 2002; Calor Gas Refrigeration Web site, 2004; CARE Web site, 2004).

In addition, HCs have been used in MVACs for the last several years. Some have estimated that, in certain parts of Australia, 280,000 vehicles contain HC refrigerants (Greenchill Web site, 2000), although independent data have not been supplied to confirm this estimate. The use of HC refrigerants in direct expansion systems not designed for a flammable refrigerant can pose safety concerns and is not considered acceptable by much of the global MVAC industry. The SAE's Alternate Refrigerant Cooperative Research Program has demonstrated a secondary loop system using HC refrigerant that minimizes the possible release of flammable refrigerant into the passenger compartment (Hill and Atkinson, 2003).

Proponents of HC systems claim that these systems bring numerous benefits, including increased energy efficiency, lower refrigerant cost, lower capital cost, and less noise (HyChill Web site, 2004; Greenchill Web site, 2000), but little independent research exists to confirm these claims. In many parts of the world, however, safety issues, public perception, and manufacturer acceptance impede further penetration of this option.

This analysis does not consider the use of HCs in household refrigeration because this option was assumed to reach maximum market penetration in the baseline. In those regions where HCs have not successfully penetrated markets (e.g., North America), the perceived risk and lack of acceptance of HC refrigerants, which has prevented adoption to date, was assumed to continue to serve as a barrier in the foreseeable future. The use of HCs in other refrigeration end-uses was not considered because of uncertainty about costs and likely market penetration.

CO₂

Another option is to use CO₂ as a refrigerant. Prototype CO₂ systems have been developed for numerous types of systems, including MVACs, industrial processing, refrigerated transport, and retail food systems. CO₂ has zero ODP and a GWP of 1, and is claimed by its proponents to be advantageous for use as a refrigerant. However, CO₂ is associated with potential safety risks and other technical and economic disadvantages. Above certain concentrations, exposure to CO₂ may result in adverse health consequences. At very high concentrations, even for short periods of time, CO₂ affects the central nervous system and is toxic. To protect against adverse health effects from workplace exposure, the Occupational Safety and Health Administration (OSHA) recommended an 8-hour time-weighted average exposure

limit of 5,000 parts per million (ppm) (ACGIH, 1999). Also, CO₂ systems operate at a high pressure, which presents a potential hazard and may increase the cost of designing and purchasing equipment. In addition, potential loss of operational efficiency and associated increases in energy use and indirect emissions, refrigerant containment issues, long-term reliability, and compressor performance are other potential problems (Environment Canada, 1998).

For this analysis, CO₂ systems were evaluated only as options for MVACs. CO₂ is being investigated for other end-uses but, because research is still in the early stage and there is little information, those end-uses were not explored in this analysis. The MVAC option is described in detail in the section on “Technology Options.”

Other Low-GWP Refrigerants

The use of other low-GWP refrigerants (e.g., HFC-152a with a GWP of 140) in place of higher-GWP refrigerants (e.g., HFC-134a with a GWP of 1,300) is another option for reducing greenhouse gas emissions. The use of HFC-152a in MVACs was explored in this cost analysis, as described in detail in the “Technology Options” section.

Several other low-GWP refrigerants exist. For example, CO₂, discussed above, has a GWP of 1. In addition, HCFC-123 and HCFC-124, which are not considered alternatives to HFCs, have low direct GWPs, but their use is complicated by other factors, including their contribution to stratospheric ozone depletion. While some studies (e.g., Calm, Wuebbles, and Jain, 1999; Wuebbles and Calm, 1997; USEPA, 2002; RTOC, 2003) suggest that the extended use of HCFC-123 in large tonnage chillers may reduce direct GWP-weighted refrigerant emissions, and in some instances may reduce overall greenhouse gas emissions, this option was not examined here because full compliance with the current HCFC phaseout schedule was assumed.

Technology Options

This section presents cost analyses for six alternative technology options, three of which apply to the stationary equipment (distributed systems, HFC secondary loop systems, and ammonia secondary loop systems), and three of which apply to mobile systems (enhanced HFC-134a, HFC-152a, and CO₂). Oil-free compressors, geothermal cooling systems, and desiccant cooling systems are also described qualitatively.

Distributed Systems for Stationary Commercial Refrigeration Equipment

A distributed system consists of multiple compressors that are distributed throughout a store, near the display cases they serve, and are connected by a water loop to a single cooling unit that is located on the roof or elsewhere outside the store. Refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional centralized direct expansion (DX) system. Significant reductions in total global warming impact from current levels may be possible with distributed systems that use HFC refrigerants (Sand et al., 1997).

Using HFC-distributed systems in lieu of HFC centralized DX systems in retail food settings offers the potential to reduce HFC emissions. Distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, with each unit sending heat to a central water cooling system. A distributed system would significantly reduce the refrigerant inventory—by an estimated 75 percent—and minimize the length of refrigerant tubing and the number of fittings that are installed in DX systems, thereby reducing HFCs leaks by an estimated 5 percent to 7 percent (IPCC/TEAP, 2005).

This technology option is assumed to be applicable to the retail food and cold storage end-uses. The project lifetime is assumed to be 15 years, and the emissions reduction efficiency is calculated to be 90

percent. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-11. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19, expressed as a percentage of emissions from new equipment, and as a percentage of emissions from all equipment (new and existing), respectively. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to penetrate only new retail food and cold storage installations (i.e., those installed in 2005 or beyond).

Table 2-11: Summary of Assumptions for Distributed Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	Retail food Cold storage	90.0%	43.1%	40.6%
Other Annex I countries			34.1%	32.1%
Latin America and Caribbean			51.7%	44.5%
China, Hong Kong, and India			28.0%	17.3%
Other non-Annex I countries, Russian Federation, and Ukraine			57.3%	46.6%

^a End-uses and reduction efficiency apply to all regions.

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning emissions that are assumed to come from retail food and cold storage end-uses.

Secondary Loop Systems for Stationary Equipment

Secondary loop systems pump cold fluid to remove heat from equipment (e.g., refrigerated food display cases) or areas to be cooled. The fluid, often a brine solution, passes through a heat exchanger to be cooled by a refrigerant isolated from the equipment or areas cooled. These systems require a significantly lower refrigerant charge, have lower leakage rates, and can allow the use of flammable or toxic refrigerants.

Secondary loops may be used in commercial and industrial refrigeration applications, for example, to cool supermarket display cases without circulating toxic or flammable refrigerants throughout the store or to reduce the needed charge of HFC refrigerants. The primary disadvantages of the secondary loop system are a loss of energy efficiency and higher capital costs. Potential benefits of secondary cooling systems, however, include decreased charge sizes, decreased leakage rates, faster defrost, lower maintenance needs, and longer shelf lives, which can result in significant cost savings over time (Bennett, 2000; Baxter, 2003; Faramarzi and Walker, 2003). Indeed, the reduction in size and leakage rate of the refrigerant charge could result in a reduced global warming impact, even with the use of fluorocarbon refrigerants. The use of zero-GWP refrigerants could result in even lower global warming impacts (Sand, et al., 1997). Furthermore, secondary loop systems have improved temperature control compared with conventional direct expansion systems, which can represent an important advantage in countries like the United States, where recent regulations on temperature control for refrigerated products such as meat, poultry, and fish have become more stringent. Moreover, recent technological improvements to secondary cooling systems, such as high-efficiency evaporative condensers and display cases with high temperature brines, have increased system efficiency (Baxter, 2003; Faramarzi and Walker, 2003). Two types of secondary loop systems, for use in retail refrigeration and cold storage warehouses, are analyzed in greater detail below.

Secondary loops could mitigate some but not all of the risks of using flammable refrigerants in residential and commercial unitary end-uses. In addition, secondary loops have potential applications in

MVACs, discussed further in “HFC-152a Refrigerant in MVACs.” Because of the lack of technical and cost information on secondary loop systems in these other applications, they are not included as options in this analysis.

HFC Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

Designing new retail food and cold storage systems to operate using secondary loops with HFCs can reduce HFC emissions. As discussed above, secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases (UNEP, 1999a; ADL, 1999). These systems have lower leakage rates and operate at reduced charges. Additionally, pipes used in these systems are now premanufactured and can be made of preinsulated plastic instead of copper. This design reduces material costs and, by eliminating the need for brazing, allows for faster installation. In the United States, installation costs have been reduced significantly in recent years. With continued research and development, this technology is expected to soon be as cost-effective to purchase, install, and operate as centralized DX systems (Bennett, 2000). This technology option is assumed to be applicable to the retail food and cold storage end-use sectors, and is expected to reduce charge size by between 75 percent and 85 percent and bring annual leakage rates down to about 5 percent (IPCC/TEAP, 2005)—reducing direct emissions from appropriate end-uses by approximately 93 percent (see calculation below). The project lifetime is assumed to be 15 years. The regional technical applicabilities for 2010 and 2020 and the reduction efficiencies are presented in Table 2-12. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to penetrate only new retail food and cold storage installations (i.e., those installed in 2005 or beyond).

Table 2-12: Summary of Assumptions for HFC Secondary Loop Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	Retail food Cold storage	93.33%	43.1%	40.6%
Other Annex I countries			34.1%	32.1%
Latin America and Caribbean			51.7%	44.5%
China, Hong Kong, and India			28.0%	17.3%
Other non-Annex I countries, Russian Federation, and Ukraine			57.3%	46.6%

^a End-uses and reduction efficiency apply to all regions.

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning emissions that are assumed to come from equipment in the retail food and cold storage end-uses.

Ammonia Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

The use of ammonia is very common in some countries, while strongly restricted in others. For example, for many decades ammonia has been used in almost all dairies, breweries, slaughterhouses, and large freezing plants across Europe, while its use has been heavily regulated in North America (ACHR News, 2000). Ammonia refrigeration has historically been used in large, low-temperature industrial refrigeration, as well as in medium and large chillers, generally for food processing (Crawford, 1999). However, the use of ammonia refrigerant is beginning to expand into retail food and smaller chillers in some countries, particularly in the EU-15.

Because of ammonia’s materials capability, toxicity, and flammability, major design modifications would be required for the majority of traditional HFC systems. Furthermore, since different countries

have different sets of building codes, fire codes, and other safety standards relating to the use of ammonia in building equipment, some countries (e.g., the United States) would need to revise those codes to allow for the expanded use of ammonia in new equipment types.

Ammonia can be used as the primary refrigerant in secondary loop systems in place of HFCs. Because ammonia secondary loop systems avoid running the primary refrigerant through miles of piping to and from food storage cases, they have lower leakage rates than conventional centralized DX systems and operate at reduced charges. In these types of systems, ammonia is kept out of public contact (e.g., outside of buildings), and nontoxic fluids are used as secondary coolants. Incremental one-time costs for ammonia systems are assumed to include expenditures for equipment needed to ensure safety. The annual operating costs also include net energy requirements, but, because of a lack of information, do not cover costs associated with training technicians and development and updating of safety protocols to handle more hazardous refrigerants, including ammonia. This technology option is assumed to be applicable to the retail food and cold storage end-uses. The project lifetime is assumed to be 15 years. The reduction efficiency of this option is 100 percent, as the ammonia completely replaces the HFC. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to be technically applicable in only new (i.e., those installed in 2005 or beyond) retail food and cold storage installations.

Table 2-13 presents the reduction efficiency and regional technical applicabilities for 2010 and 2020.

Table 2-13: Summary of Assumptions for Ammonia Secondary Loop Systems for New Stationary Equipment

Country/Region	Applicable End-Use Sector(s) ^a	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	Retail food Cold storage	100.0%	43.1%	40.6%
Other Annex I countries			34.1%	32.1%
Latin America and Caribbean			51.7%	44.5%
China, Hong Kong, and India			28.0%	17.3%
Other non-Annex I countries, Russian Federation, and Ukraine			57.3%	46.6%

^a End-uses and reduction efficiency apply to all regions.

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning emissions that are assumed to come from equipment in the retail food and cold storage end-uses.

Ammonia systems are assumed to penetrate a greater percentage of non-U.S. markets as a result of different safety standards and greater acceptance by industry, end-users, regulators, and insurance companies in those countries. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

Enhanced HFC-134a Systems in MVACs

Various options exist to reduce emissions of HFC-134a in MVACs by reducing charge size, leakage rates, or system efficiency (i.e., reducing system power consumption). Specifically, reducing the volume of the system components, such as the condenser and refrigerant lines, can reduce charge size. Similarly, leakage rates can be lowered and system efficiency improved by using better system components, such as improved system sealing, lower permeation hoses, improved fittings, and higher evaporator temperatures (Lundberg, 2002; Xu and Amin, 2000). Additional savings of indirect emissions can be obtained by improving system efficiency, for example through the use of oil separators and externally controlled swashplate compressors.

Based on the latest science and industry estimates available when this analysis was performed, enhanced HFC-134a systems can reduce baseline direct emissions by 50 percent (SAE, 2003a). This technology is not expected to become commercial until after 2006 (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 2-14.

Table 2-14: Summary of Assumptions for Enhanced HFC-134a Systems for New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	MVACs	50.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

^a Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems) as a result of reduced leakage.

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

Acceptance of this substitute would likely vary by region, based on consumer and industry attitudes, economic variables, and availability of competing options. Enhanced HFC-134a systems are expected to become commercially available several years before other alternatives (e.g., CO₂ and HFC-152a). Therefore, this analysis assumes that, initially, enhanced HFC-134a systems will begin to penetrate the markets of developed countries—with the exception of Europe, which is expected to move away from HFC-134a use in MVACs in response to new EC legislation.²¹ In developed countries such as the United States, Japan, and Canada, where the industry is resistant to switching from HFC-134a and/or regulations phasing out the use of HFC-134a in MVACs do not exist, this option is assumed to gain the greatest market penetration. In developing countries, capital cost is expected to prevent this option from significantly penetrating the market before 2010; however, given the global market, these systems are expected to gain market share by 2020. The cost analysis for this option does not include any costs associated with retrofitting existing HFC-134a systems. Therefore, this option is assumed to penetrate only new MVACs produced after 2004. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

HFC-152a Refrigerant in MVACs

Replacing HFC-134a refrigerant in MVACs with HFC-152a represents a significant opportunity to reduce GWP-weighted HFC emissions, since the GWP of HFC-152a is 140, 89 percent less than that of HFC-134a, whose GWP is 1,300. HFC-152a is a flammable refrigerant but is less flammable than HCs. HFC-152a can be used in DX and secondary loop MVAC systems. Because there is still great uncertainty associated with the future costs of HFC-152a secondary loop systems for MVACs, this cost analysis only considers the DX option. Likewise, because there is still great uncertainty associated with future costs of improved HFC-152a MVACs, only the conventional DX systems are considered in this cost analysis. However, like the enhanced HFC-134a system discussed above, HFC-152a MVACs will use improved

²¹ According to the EC Directive, HFC-134a will be phased out from 2011 onward for new vehicle models and from 2017 for all new vehicles. The directive applies to gases with a GWP higher than 150 (EC, 2004).

system components to further reduce refrigerant leakage rates and increase system efficiency (e.g., externally controlled variable displacement compressors).

In addition to direct emissions reductions associated with a lower GWP, HFC-152a DX systems in MVACs also reduce indirect emissions by improving system efficiency by about 10 percent (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 2-15.

Table 2-15: Summary of Assumptions for HFC-152a DX Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	MVACs	89.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

^a Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems) as a result of lower GWP.

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

The use of HFC-152a DX systems in MVACs would not require any significant changes to existing HFC-134a system components apart from a safety mitigation system (e.g., a refrigerant detector and a valve to isolate the remaining charge from the passenger compartment), thereby rendering this option easy to introduce into the market. Furthermore, compared with baseline HFC-134a systems, HFC-152a systems are expected to be more efficient and may operate at reduced refrigerant charges and leakage rates.²² However, because HFC-152a is a slightly flammable gas, safety systems are needed. Thus, personnel training would be needed to enable the safe and effective recovery and recycling of refrigerant at service and disposal, and additional safety systems to minimize the potential for large leaks into the passenger compartment may be required. New fire-safe service equipment for refrigerant recovery and charging and leak detection may also be required.

While the MVAC industry has demonstrated the use of HFC-152a in prototype DX (and secondary loop) MVAC systems, the technology is still in the research and development phase. HFC-152a systems are expected to become commercially available between 2006 and 2008 (SAE, 2003a). Once available, it is assumed that, initially, HFC-152a systems will gain market share in developed countries, although use in Europe will be tempered by conditions that may favor CO₂ systems. Market penetration in developing countries is expected to lag by about 5 years. Retrofitting HFC-134a systems to HFC-152a systems is not considered technically or economically feasible, because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the system. Thus, costs associated with retrofit were not assessed, and this option is assumed to penetrate only new MVACs produced after 2004. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

²² Because these systems are still under development, this cost analysis does not consider the possible reduction in charge and leakage rates, although efficiency improvement predictions based on SAE (2003a) are included.

CO₂ in MVACs

Systems that use CO₂ as the refrigerant in MVACs represent a potential opportunity for emissions reduction. This technology uses a transcritical vapor cycle that differs from conventional MVAC systems and requires innovative design and engineering. The arrangement of components in CO₂ systems is generally consistent with conventional systems; however, a suction line heat exchanger is added and a low side accumulator is used (in place of a high side receiver, which is used in most conventional HFC-134a systems). In addition, the individual system components are designed to reflect the extremely high pressure levels of supercritical CO₂ (about 2,000 pounds per square inch [psig]).

Because CO₂ has a GWP of 1, its use would virtually eliminate the climate impacts of direct refrigerant emissions from MVACs. CO₂ systems perform most efficiently in areas like northern Europe that require air conditioners for cooling and other purposes, but generally have mild ambient temperatures.²³ In addition, heat pump technology for vehicles is under development (VDA, 2003), which may allow CO₂ systems to be used for supplemental heating of the passenger compartment (SAE, 2003a). This technology may be an important function in cars with very efficient engines, where minimal waste heat is available to warm the passenger compartment.

While CO₂ has the advantage of being non-flammable, it is toxic. A short exposure to elevated levels of CO₂ can lead to dizziness, drowsiness, and even death (Lambertsen, 1971; Wong, 1992). In addition, CO₂ system operating pressure is 5 to 10 times that of HFC-134a; therefore, appropriate safety features and new system and component designs are required before this option can be brought to market. Furthermore, an internal heat exchanger, which would further cool the high-temperature CO₂ from the gas cooler and heat the low-temperature CO₂ from the accumulator, would be needed to increase cooling capacity and energy efficiency to acceptable levels. Also, in the event of a large leak, passengers could be exposed to potentially dangerous levels of CO₂; thus, it is assumed that safety systems designed to minimize passenger exposure would be incorporated into the system design.

Several engineering constraints must still be overcome, including those associated with flexible lines, increased system weight, and system leakage and leak detection methods. In addition, because these systems will be designed and built differently than current MVACs and because the high pressure presents additional risks, technicians will need to be trained on how to service and maintain these new systems safely and correctly in order to prevent safety hazards and maintain system performance. New service equipment for refrigerant charging and leak detection may also be required. Moreover, because of the high pressure of these systems and toxicity concerns, MVAC servicing and maintenance would need to be performed by skilled technicians, to prevent safety hazards and maintain system performance.

The efficiency gains associated with CO₂ systems are between 20 and 25 percent (SAE, 2003a). In this cost analysis, 22.5 percent is used for calculation purposes. While there are ongoing efforts to develop improved CO₂ systems for MVACs—which experts predict would exceed this 20 to 25 percent energy efficiency gain—much uncertainty remains regarding the investment costs required to manufacture these systems. Therefore, these improved CO₂ systems are not considered further in this analysis. The assumed project lifetime (i.e., MVAC lifetime) is 12 years. Regional technical applicabilities and the reduction efficiency for the CO₂ option are presented in Table 2-16.

²³ Compared with other refrigerant technologies, prototype CO₂ MVAC systems are not as efficient in warmer climates. The MVAC industry is actively pursuing research and development activities to improve system efficiency in warmer weather conditions (SAE, 2003b).

Table 2-16: Summary of Assumptions for CO₂ Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency ^a	Technical Applicability ^b	
			2010	2020
United States and Japan	MVACs	100.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

^a Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems).

^b Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

CO₂ systems may be available on the market in the next few years (SAE, 2003a). In light of the new EC directive on MVACs, and because European manufacturers are most aggressively pursuing CO₂, this option is expected to become the dominant market player in this market. In other developed countries, such as the United States, Australia, New Zealand, and Canada, the industry is not developing this technology as aggressively, and it is assumed that this option will not be widely adopted in these markets in the near future. Finally, because of the high capital costs associated with this option (see details below), this technology is also not expected to be adopted in developing countries until later years, assuming a projected global market shift to non-GWP alternatives. The project lifetime is assumed to be 12 years, and assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19. Retrofitting HFC-134a systems to CO₂ is not considered technically or economically feasible because of the high operating pressures and because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the systems. Thus, costs to retrofit were not assessed, and this option is assumed to penetrate only new MVACs produced after 2004.

Oil-Free Compressors

Oil-free compressors are available for chillers, industrial process applications, and other applications where compressors are used. The elimination of oil in refrigeration and air-conditioning compressors has been achieved through various innovative designs, including the incorporation of magnetic or hybrid ceramic bearings (SKF, 2003; Smithart, 2003). In some systems, oil may decrease heat transfer and reduce operating efficiency; therefore, removing oil may increase the ability to sustain system efficiency over the life of the equipment. This reduction will lower indirect emissions of CO₂ associated with electricity production. Eliminating the use of oil in compressors can reduce the number of equipment components (e.g., oil separators and sealing, fittings, and connections), allowing equipment to be made tighter, resulting in lower leakage rates. In addition, oil-free compressors remove the need for oil changes and the associated refrigerant emissions that may be experienced through the service practices used or from refrigerant dissolved in the oil. However, this potential emissions reduction may be offset by an increased frequency of compressor and bearing inspection or replacement (Digmanese, 2004), although an increasing history of operation may prove that unnecessary. This option was not included in the cost analysis because limited data were available.

Geothermal Cooling Systems

In some locations, geothermal cooling systems for residential and commercial spaces are popular and economically sound as an alternative to conventional air-conditioning systems. Geothermal technology transfers heat between the system and the earth and can provide both space heating and cooling. Though

installation costs for geothermal systems are typically 30 percent to 50 percent higher than for conventional systems, annual costs are reduced by 20 percent to 40 percent because of increased energy efficiency. Economic paybacks can accrue in as little as 3 to 5 years. Geothermal systems may save homeowners 20 percent to 50 percent in cooling costs (Geoexchange, 2000; Rawlings, 2000). Because of a lack of cost and market penetration data, this technology is not considered further in this analysis.

Desiccant Cooling Systems

Desiccant cooling is produced by removing moisture from an air stream using a desiccant and then separately cooling the dry air. The desiccant is thermally regenerated, typically by burning natural gas or by capturing excess heat. Desiccant cooling may replace the latent cooling done by some end-uses, such as unitary systems. Integrated desiccant cooling systems that combine a desiccant system with a vapor compression or other cooling system have been successfully installed in some commercial buildings (Fisher, Tomlinson, and Hughes, 1994). However, current designs are used primarily in niche markets that require precisely controlled humidity or low humidity levels, such as hospital operating rooms and certain industrial processes. For desiccant-based systems to be considered widely feasible in the commercial air-conditioning market, improvements in efficiency, cost, size, reliability, and life expectancy must be made (Sand et al., 1997).

Desiccant systems have also been tried in MVAC systems, but were found technically and economically infeasible. These systems require an intermittent source of heat; however, because new automobiles produce very little waste heat, there is not enough heat for a desiccant system to function. Desiccant systems may only be feasible where there is a large heat source, such as a large truck or bus (Environment Canada, 1998). Furthermore, in order for desiccant air-conditioners to become viable options for MVACs, the varying heat source must be controlled during normal driving conditions when vehicle speed is continually changing. Current prototypes are large and heavy, and the systems have not been shown to be cost-effective or durable enough to justify the initial investment (USEPA, 2001a).

Because of the technical barriers and insufficient cost information associated with the feasibility of this option, desiccant cooling systems were not explored further in this analysis.

Absorption Systems

Absorption systems refrigerate or cool using two fluids and some quantity of heat input, rather than using electrical input. Specifically, absorption systems use a secondary fluid or absorbent to circulate the refrigerant (Rafferty, 2003). These systems can be used in residential refrigeration and chiller applications and, potentially, in heat pumps in residential and light commercial applications, as described below.

- **Refrigeration Systems.** In the late 1990s, more than 1 million of an estimated 62 million refrigerators sold annually were thermally activated ammonia or water absorption systems (Sand et al., 1997). The refrigerants used for absorption refrigeration have negligible GWPs. Absorption refrigeration is commonly used in hotel rooms and for recreational vehicles because the process operates quietly and can use bottled gas for energy. Absorption refrigerators are limited in size because of design constraints. Through design improvements, the thermal coefficient of performance (COP) of these refrigerators can be increased by as much as 50 percent from a COP of 0.2 to 0.3 without degrading cooling capacity (Sand et al., 1997). However, the low efficiency of absorption equipment means that the indirect emissions must be carefully analyzed. Inherent design limitations make it unlikely that absorption refrigeration will become a significant replacement for vapor compression refrigerators. Still, absorption refrigeration has great capacity and operating attributes that permit the technology to fill niche markets (Sand et al., 1997).

- **Chillers.** Gas-fired (as opposed to electrically powered) absorption water chillers are sold in the United States and Japan. These systems are used primarily where there is a relatively short cooling season, where electricity costs (especially demand charges) are high, or where fairly high-grade waste heat is available. Although absorption chillers are far less efficient than competitive systems if waste heat is unavailable, the technology is feasible and, under some economic circumstances, compares favorably with vapor compression chillers using fluorocarbon refrigerants. Market success will be determined by factors such as the relative costs of natural gas and electricity, peak load charges, and purchase costs. In addition, absorption chillers currently have higher capital costs than vapor compression equipment, such that significant operating cost savings would be necessary to make their purchase economically competitive.
- **Heat Pumps.** Research and development efforts are attempting to create absorption heat pumps for heating and cooling in residential and light commercial applications. Several years ago in Europe and the United States, generator absorber heat exchange (GAX) ammonia-water absorption heat pumps were being developed and in Japan field test units had been built. Absorption heat pumps could be used to reduce global warming impacts in areas where heating load dominates, although the pumps would have the opposite effect in areas where cooling dominates (Sand et al., 1997).

Because these options are either still under development or are primarily optimal in niche markets, sufficient information was not available to include their costs and reduction potential in this analysis.

IV.2.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 2-19 summarizes the percentage of total refrigeration and air-conditioning sector emissions that may be technically abated by each of the options explored in this analysis, based on the percentage of sector emissions from each end-use (which varies by region), as provided in Table 2-6. Market penetration values for each abatement option were developed for each region, when possible, to best reflect qualitative information available on region-specific realities and possible future action. The commercial refrigeration and MVAC technology options explored in this chapter are assumed to penetrate only new (not existing) equipment, where new equipment is defined as equipment manufactured in 2005 or later. Table 2-18 presents the assumed maximum market penetration for the technology options into equipment manufactured in 2005, 2010, 2015, and 2020. Table 2-19 presents the final maximum penetration into the installed base of equipment, taking into account the percentage of each market that is new (i.e., manufactured in 2005 or beyond) in all preceding years. Values from Table 2-19 are multiplied by technical applicabilities (Table 2-17) and the reduction efficiency to generate the percentage reduction off baseline emissions for each option, as presented in Table 2-20. The text box provided in Section IV. 2.4 provides further explanation on how the results (i.e., percentage reduction off baseline emissions) are calculated.

IV.2.4 Results

Emissions reduction potential for abatement options varies by region based on assumed end-use breakouts (provided in Table 2-6) and on qualitative information regarding current and future likelihood of market penetration by region. The percentage reduction from the baseline associated with each abatement option is calculated by multiplying the technical applicability (from Table 2-17) by both the incremental maximum market penetration (from Table 2-18) and the reduction efficiency. For more

information on how emissions reductions are calculated for each option, please see the text box below, which presents an illustrative example of the emissions reduction methodology.

Calculating Emissions Reductions for Each Abatement Option

The equation used to derive total emissions reductions off the baseline for each option is as follows:

$$\text{Emissions Reduction} = \text{technical applicability} \times \text{incremental maximum market penetration (expressed as percentage of entire installed base)} \times \text{reduction efficiency}$$

The following table provides a sample calculation using the option of leak repair for large equipment in the United States in 2020 as an example.

Sample Calculation of Emissions Reductions: Leak Repair for Large Equipment—United States (2020)

Sample Calculation of Emissions Reductions: Leak Repair for Large Equipment							United States (2020)
Applicable End-Uses (Table 2-9)	Technical Applicability ^a (Based on Tables 2-6 and 2-9)		Incremental Maximum Market Penetration (Table 2-19)		Reduction Efficiency (Table 2-9)		Percentage Reduction from 2020 Baseline (Table 2-20)
Chillers	1.5 × 50%		5%		40%		0.02
Retail food	39.1 × 50%		5%		40%		0.39
Cold storage	1.4 × 50%		5%		40%		0.01
Industrial process	6.6 × 50%		5%		40%		0.07
Total	48.7 × 50%	×	5%	×	40%	=	0.49 ^b

^a For each country/region, technical applicability varies based on the percentage of sector emissions from applicable end-uses, as provided in Table 2-6. Additionally, for the leak repair and refrigerant recovery and recycling options, only half of the emissions from applicable end-uses (i.e., large end-uses for leak repair and small end-uses for recovery and recycling) are assumed to be abatable; for all other options, 100 percent of emissions from new (post-2004) equipment in applicable end-uses are assumed to be abatable.

^b Total may not sum due to independent rounding.

Table 2-21 presents a summary of the cost assumptions used for the refrigeration/air-conditioning options presented in the discussions above.

IV.2.4.1 Data Tables and Graphs

Tables 2-22 and 2-23 provide a summary of the potential emissions reductions at various breakeven costs by country/region in 2010 and 2020, respectively. The costs to reduce 1 tCO₂eq are presented at a 10 percent discount rate and 40 percent tax rate. Table 2-24 presents the potential emissions reduction opportunities and associated annualized costs for the world in 2020 ordered by increasing costs per tCO₂eq, using the highest cost in the region. Because many of the options analyzed affect indirect (CO₂ from energy generation) emissions, the net (HFC + CO₂) emissions reduced by each option are presented. The direct (HFC) emissions reduced by the option and a cumulative total of direct emissions reduced, in MtCO₂eq and percentage of the regional refrigeration and air-conditioning baseline, are also presented. Figures 2-2 and 2-3 present MACs for this sector at 10 percent discount rates and 40 percent tax rates in 2010 and 2020, respectively.

Table 2-17: Summary of Technical Applicability of Abatement Options by Region (Percent)^a

Abatement Option	United States and Japan				China, Hong Kong, and India				Europe, Australia, New Zealand, and All Other Annex I Countries				Latin America and Caribbean				Russian Federation, Ukraine, and All Non-Annex I Countries			
	2005	2010	2015	2005	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Refrigerant recovery from small equipment	26.0	24.3	24.6	25.7	28.1	33.3	37.5	39.6	30.1	29.7	27.6	30.7	17.9	19.2	21.3	23.3	14.0	15.8	19.0	22.1
Leak repair for large equipment	24.0	25.7	25.4	24.3	21.9	16.7	12.5	10.4	19.9	20.3	22.4	19.3	32.1	30.8	28.7	26.7	36.0	34.2	31.0	27.9
Ammonia secondary loop	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
Distributed system	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
HFC secondary loop system	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
Enhanced HFC-134a in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0
HFC-152a in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0
CO ₂ in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0

^a Expressed as a percentage of total refrigeration and air-conditioning emissions.

Table 2-18: Assumed Regional Market Penetration of Abatement Options into Newly Manufactured Equipment, Expressed as a Percentage of Emissions from New Equipment^a

	United States				Europe ^b				Japan, Australia, & New Zealand				All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean, Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																								
Refrigerant recovery from small equipment		ND				ND				ND				ND				ND				ND		
Leak repair for large equipment		ND				ND				ND				ND				ND				ND		
Technology Options																								
Ammonia secondary loop	3	5	13	20	5	10	13	15	5	10	13	15	5	10	13	15	5	10	10	10	5	10	10	10
Distributed system	8	15	23	30	10	20	30	40	10	20	30	40	10	20	30	40	8	15	20	25	8	15	20	25
HFC secondary loop system	8	15	23	30	5	10	18	25	5	10	18	25	5	10	18	25	8	10	13	20	8	10	13	20
Enhanced HFC-134a in MVACs	0	40	50	60	0	0	0	0	0	40	50	60	0	40	50	60	0	5	20	40	0	5	20	40
HFC-152a in MVACs	0	1	20	30	0	1	15	25	0	1	20	30	0	1	20	30	0	0	1	20	0	0	1	20
CO ₂ in MVACs	0	1	5	10	0	15	65	75	0	1	5	10	0	1	5	10	0	0	1	5	0	0	1	5

^a Expressed as a percentage of new equipment for the given year. The baseline market penetration of all technology options is assumed to be zero so that only incremental market penetration is analyzed.

^b Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia. ND: No distinction was made between market penetration assumptions into new versus existing equipment.

Table 2-19: Market Penetration of Abatement Options, Expressed as a Percentage of Total Sector Emissions^a

	United States				Europe ^c				Japan, Australia, & New Zealand				All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean, Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																								
Refrigerant recovery from small equipment ^b	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	20.0	30.0	40.0	50.0	20.0	30.0	40.0	50.0
Leak repair for large equipment	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	5.0	10.0	12.0	15.0	5.0	10.0	12.0	15.0
Technology Options																								
Ammonia secondary loop	0.2	1.4	4.3	9.4	0.3	2.6	6.1	10.3	0.3	2.6	6.1	10.3	0.3	2.6	6.1	10.3	0.3	2.6	5.6	8.5	0.3	2.6	5.6	8.5
Distributed system	0.5	4.1	9.9	17.9	0.6	5.3	12.9	23.5	0.6	5.3	12.9	23.5	0.6	5.3	12.9	23.5	0.5	4.1	9.4	16.1	0.5	4.1	9.4	16.1
HFC secondary loop system	0.5	4.1	9.9	17.9	0.3	2.6	7.0	13.5	0.3	2.6	7.0	13.5	0.3	2.6	7.0	13.5	0.5	3.2	6.6	11.7	0.5	3.2	6.6	11.7
Enhanced HFC-134a in MVACs	0.0	10.0	29.2	48.5	0.0	0.0	0.0	0.0	0.0	10.0	29.2	48.5	0.0	10.0	29.2	48.5	0.0	1.3	7.1	19.9	0.0	1.3	7.1	19.9
HFC-152a in MVACs	0.0	0.3	5.4	16.2	0.0	0.3	4.2	12.8	0.0	0.3	5.4	16.2	0.0	0.3	5.4	16.2	0.0	0.0	0.3	5.4	0.0	0.0	0.3	5.4
CO ₂ in MVACs	0.0	0.3	1.7	4.9	0.0	3.8	22.5	50.6	0.0	0.3	1.7	4.9	0.0	0.3	1.7	4.9	0.0	0.0	0.3	1.7	0.0	0.0	0.3	1.7

^a Total sector emissions include those from new and existing equipment (i.e., the entire installed base). The baseline market penetration is assumed to be zero, unless otherwise noted.

^b Shown percentage values are incremental relative to the baseline market penetration, which is assumed to be 80 percent in developed countries and 30 percent in developing countries.

^c Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia.

Table 2-20: Percentage of (Direct)^a Reduction Off Baseline Emissions of All Abatement Options by Region

	United States				Europe ^b				Japan				Australia and New Zealand			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																
Refrigerant recovery from small equipment	1.1	2.1	2.1	3.3	1.3	2.5	2.4	3.9	1.1	2.1	2.1	3.3	1.3	2.5	2.4	3.9
Leak repair for large equipment	0.3	0.3	0.5	0.5	0.2	0.2	0.4	0.4	0.3	0.3	0.5	0.5	0.2	0.2	0.4	0.4
Technology Options																
Ammonia secondary loop	0.1	0.6	1.8	3.8	0.1	0.9	2.3	3.3	0.1	1.1	2.6	4.2	0.1	0.9	2.3	3.3
Distributed system	0.2	1.6	3.8	6.5	0.2	1.6	4.4	6.8	0.2	2.1	5.0	8.6	0.2	1.6	4.4	6.8
HFC secondary loop system	0.2	1.6	3.9	6.8	0.1	0.8	2.5	4.1	0.1	1.1	2.8	5.1	0.1	0.8	2.5	4.1
Enhanced HFC-134a in MVACs	0.0	1.4	3.3	4.8	0.0	0.0	0.0	0.0	0.0	1.4	3.3	4.8	0.0	2.1	4.6	8.9
HFC-152a in MVACs	0.0	0.1	1.1	2.9	0.0	0.1	1.2	4.2	0.0	0.1	1.1	2.9	0.0	0.1	1.5	5.3
CO ₂ in MVACs	0.0	0.1	0.4	1.0	0.0	1.6	7.2	18.5	0.0	0.1	0.4	1.0	0.0	0.1	0.5	1.8
	All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean				Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																
Refrigerant recovery from small equipment	1.3	2.5	2.4	3.9	4.8	8.5	12.8	16.8	3.0	4.9	7.3	9.9	2.4	4.0	6.5	9.4
Leak repair for large equipment	0.2	0.2	0.4	0.4	0.4	0.7	0.6	0.6	0.6	1.2	1.4	1.6	0.7	1.4	1.5	1.7
Technology Options																
Ammonia secondary loop	0.1	0.9	2.3	3.3	0.1	0.7	1.2	1.5	0.2	1.4	2.7	3.8	0.2	1.5	2.9	4.0
Distributed system	0.2	1.6	4.4	6.8	0.2	1.0	1.8	2.5	0.2	1.9	4.0	6.5	0.3	2.1	4.4	6.8
HFC secondary loop system	0.1	0.8	2.5	4.1	0.2	0.8	1.3	1.9	0.2	1.5	3.0	4.9	0.3	1.7	3.2	5.1
Enhanced HFC-134a in MVACs	0.0	2.1	4.6	8.9	0.0	0.3	2.2	6.6	0.0	0.1	0.4	1.2	0.0	0.0	0.2	0.8
HFC-152a in MVACs	0.0	0.1	1.5	5.3	0.0	0.0	0.1	3.2	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.4
CO ₂ in MVACs	0.0	0.1	0.5	1.8	0.0	0.0	0.2	1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1

^a Direct reductions refer to HFC emissions reductions; indirect emissions impacts associated with energy consumption are not reflected in this table (and are not included in the baseline).

^b Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia.

Table 2-21: Summary of Abatement Option Cost Assumptions (2000\$)

Option	Time Horizon (Years)	Unit of Costs	U.S. One-Time Cost	U.S. Annual Cost	U.S. Annual Savings	Net U.S. Annual Costs
Refrigerant recovery	1	Per recovery job	— ^a	\$10.10	\$13.71	–\$3.61
Distributed system	15	Per 60,000 ft ² supermarket	\$7,200.00	\$2,796.19 ^b	\$3,559.94	–\$763.75
Secondary loop	15	Per 60,000 ft ² supermarket	\$25,200.00	\$5,592.38 ^b	\$3,691.79	\$1,900.59
Ammonia secondary loop	15	Per 60,000 ft ² supermarket	\$36,000.00	\$5,592.38 ^b	\$3,955.49	\$1,636.89
Leak repair	1	Per repair job	\$1,480.00 ^c	—	\$2,636.99	– \$2,636.99
CO ₂ for new MVACs	12	Per MVAC	\$105.30	—	\$18.35 ^d	–\$18.35
Enhanced HFC-134a in MVACs	12	Per MVAC	\$42.12	—	\$21.38 ^d	–\$21.38
HFC-152a in MVACs	12	Per MVAC	\$23.69	—	\$7.92 ^e	–\$7.92

^a The cost of a high-pressure recovery unit is assumed to be approximately \$860, but all costs associated with this option, including capital costs, are annualized and expressed in terms of cost per job.

^b In all other countries, this annual cost was adjusted by average electricity prices (average of 1994–1999) based on USEIA (2000).

^c Includes parts and labor to perform repair job.

^d Annual U.S. costs savings are associated with gasoline and refrigerant savings. For all other countries, the annual saving associated with gasoline in the United States is adjusted by the estimated amount of gasoline saved per vehicle per year (based on Rugh and Hovland [2003]) and by average regional costs of unleaded gasoline in 2003 (based on USEIA [2005]). No adjustments are made to the savings associated with refrigerant.

^e Annual U.S. costs savings are associated with gasoline savings. For all other countries, this annual savings is adjusted by the estimated amount of gasoline saved per vehicle per year (based on Rugh and Hovland [2003]) and by average regional costs of unleaded gasoline in 2003 (based on USEIA [2005]).

Table 2-22: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.69	1.04	1.37	1.37	1.37	1.37
Annex I	9.08	17.51	18.63	18.63	19.34	19.38
Australia/New Zealand	0.09	0.20	0.27	0.27	0.27	0.27
Brazil	0.42	0.75	0.76	0.76	0.76	0.76
China & Hong Kong	2.63	3.03	3.12	3.12	3.12	3.12
Eastern Europe	0.15	0.27	0.27	0.27	0.34	0.34
EU-15	1.08	2.25	2.36	2.36	2.97	2.97
India	0.24	0.29	0.31	0.31	0.31	0.31
Japan	1.22	1.91	2.63	2.63	2.63	2.65
Mexico	0.40	0.72	0.73	0.73	0.73	0.73
Non-OECD Annex I	0.62	0.90	0.91	0.91	0.94	0.94
OECD	9.86	19.32	20.44	20.44	21.12	21.16
Russian Federation	0.52	0.74	0.75	0.75	0.75	0.75
South & SE Asia	0.79	1.57	1.57	1.57	1.57	1.57
United States	5.67	11.44	11.44	11.44	11.44	11.44
World Total	16.60	29.20	31.03	31.03	31.73	31.77

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 2-23: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	2.26	4.06	5.73	5.73	5.73	5.76
Annex I	43.63	109.62	117.89	117.89	130.65	131.50
Australia/New Zealand	0.24	1.03	1.81	1.81	1.81	1.91
Brazil	1.38	3.19	3.41	3.41	3.41	3.43
China & Hong Kong	12.33	14.41	20.41	20.41	20.41	21.09
Eastern Europe	0.81	1.66	1.66	1.66	2.96	2.96
EU-15	4.95	12.48	13.22	13.22	24.03	24.03
India	0.94	1.18	1.79	1.79	1.79	1.85
Japan	3.87	9.03	13.22	13.22	13.22	13.66
Mexico	1.29	2.99	3.19	3.19	3.19	3.22
Non-OECD Annex I	2.89	4.49	4.74	4.74	5.25	5.28
OECD	45.69	117.04	125.65	125.65	137.90	138.79
Russian Federation	2.39	3.60	3.76	3.76	3.76	3.78
South & SE Asia	3.11	7.56	7.89	7.89	7.89	7.93
United States	30.26	78.05	78.05	78.05	78.05	78.05
World Total	73.22	161.70	181.11	181.11	193.94	195.80

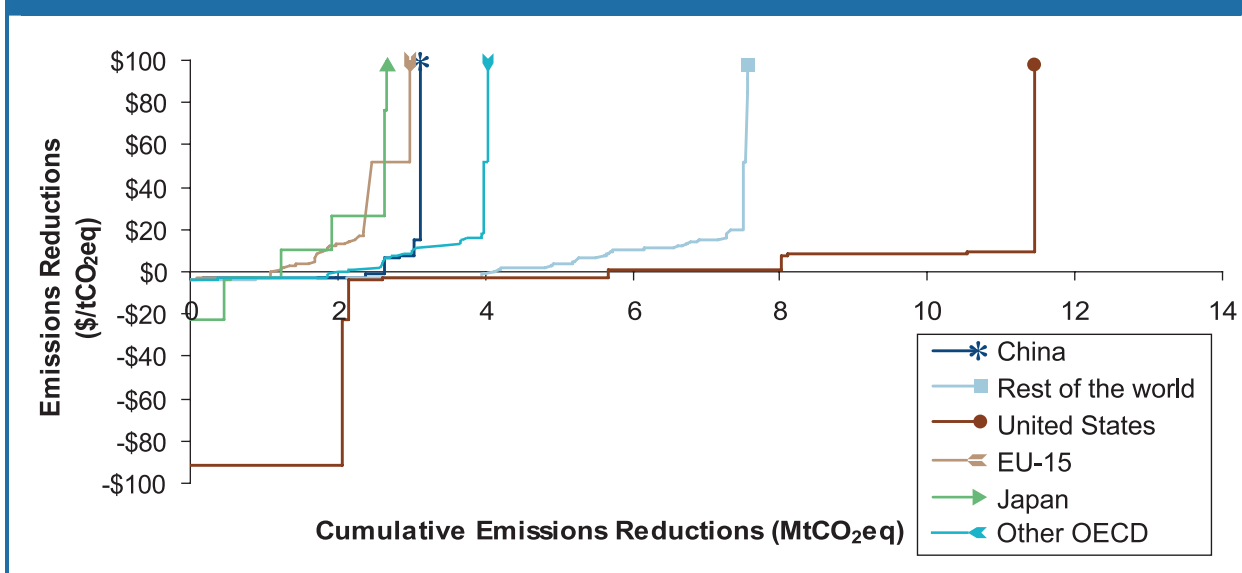
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 2-24: World Breakeven Costs and Emissions Reductions in 2020 for Refrigeration/Air-Conditioning

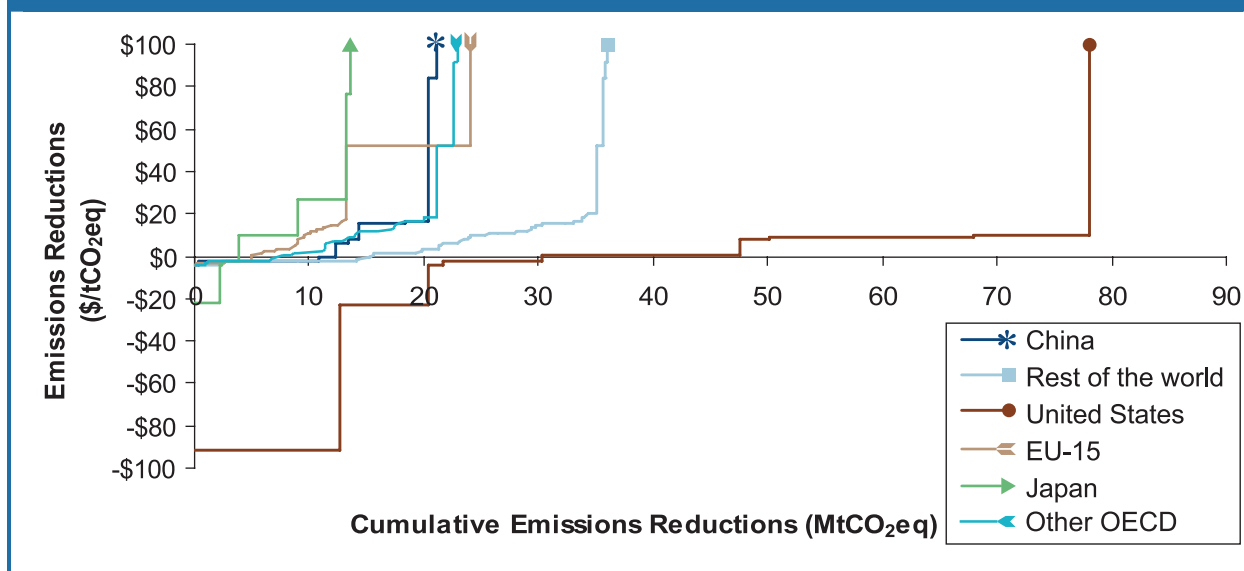
Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Direct Emissions Reduction ^a (MtCO ₂ eq)	Indirect Emissions Reduction ^b (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High					
Leak repair	-\$4.10	-\$4.10	4.91	0.00	0.8%	4.91	0.8%
Refrigerant recovery	-\$2.62	-\$2.62	40.16	0.00	6.4%	45.07	7.2%
Distributed system	-\$1.08	\$9.99	39.67	-0.43	6.3%	84.74	13.5%
Enhanced HFC-134a in MVACs	-\$175.92	\$16.21	22.69	21.67	3.6%	107.44	17.1%
HFC-152a in MVACs	-\$27.59	\$18.18	15.72	0.81	2.5%	123.16	19.6%
Ammonia secondary loop	\$6.33	\$26.40	22.18	-2.71	3.5%	145.34	23.2%
HFC secondary loop	\$4.81	\$26.70	33.20	-0.06	5.3%	178.54	28.5%
CO ₂ for new MVACs	\$7.57	\$91.60	17.26	1.83	2.8%	195.80	31.2%

^a Direct reductions refer to HFC emissions reductions (off the baseline).

^b Indirect emissions impacts are those associated with energy consumption (not included in the baseline).

Figure 2-2: 2010 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Figure 2-3: 2020 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

IV.2.4.2 Uncertainties and Limitations

This section focuses on the uncertainties and limitations of the cost estimates presented in this analysis. One significant area of uncertainty is how capital costs for these mitigation technologies may vary internationally. The analysis is currently limited by the lack of this specificity on region-specific cost analysis estimates. In addition, the main uncertainties related to the following abatement options are listed below.

Leak Repair for Large Equipment

Because leak repair can be performed on many different equipment types and can involve many different activities/tools, it is difficult to determine an average cost of such repairs or the average emissions reduction associated with them. This analysis, therefore, relies on broad assumptions available in the published literature, which may not reflect specific or even average values for the leak repair activities modeled.

Refrigerant Recovery for Small Equipment

Estimates of the amount of refrigerant recoverable from MVACs and small appliances at service and disposal are highly uncertain. This analysis uses the estimates provided in USEPA (1998).

Stationary Technology Options (Distributed, HFC Secondary Loop, and Ammonia Secondary Loop Systems)

This analysis assumes that emissions savings equal to 56 percent of the original equipment charge are realized at disposal in the distributed and HFC and ammonia secondary loop options; however, the actual amount of charge emitted at disposal is uncertain.

IV.2.5 Summary

Baseline HFC emissions from refrigeration and air-conditioning are expected to grow significantly between 2005 and 2020, as HFCs become used increasingly throughout the world to replace gases phased

out under the Montreal Protocol. The highest percentage of emissions growth is expected to occur in developing countries.

This analysis considers the costs and emissions reduction potential of eight practice and technology emissions mitigation options: (1) leak repair for large equipment, (2) refrigerant recovery and recycling from small equipment, (3) distributed system, (4) HFC secondary loop, (5) ammonia secondary loop, (6) enhanced HFC-134a systems in MVACs, (7) HFC-152a systems in MVACs, and (8) CO₂ systems in MVACs. The costs and emissions reduction benefits of each option were compared for each region. Increasing leak repair of large equipment and refrigerant recovery/recycling from small equipment represent cost-effective options for reducing emissions from stationary equipment worldwide. For MVACs, the enhanced HFC-134a option represents the most cost-effective alternative for reducing emissions.

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IV.3 HFC, HFE, and PFC Emissions from Solvents

IV.3.1 Introduction

ODSs have been used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning (UNEP, 1999a). CFCs (in particular CFC-113), methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent, carbon tetrachloride (CCl₄), were historically used as solvents in the United States. Similar usage occurred elsewhere, except in India and China, where greater volumes of CCl₄ were consumed.

To comply with the requirements of the Montreal Protocol,¹ many countries started using HCFCs, and aqueous and semiaqueous not-in-kind (NIK) solvents, as substitutes for ODSs. For example, the majority of metal cleaning end-users and some of the electronics and precision cleaning solvent end-users have already transitioned to no-clean, semiaqueous cleaning, and aqueous cleaning alternative methods. Many of the in-kind replacement solvents, including HFCs and PFCs, have also taken a share of the substitute market because they have high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These HFCs and PFCs have 100-year GWPs ranging from 890 to 7,400² and relatively low boiling points (50°C to 90°C) that contribute to their inadvertent release to the atmosphere. The replacement solvent technologies used globally are summarized in Table 3-1.

HFC solvents include HFC-4310mee, HFC-365mfc, and HFC-245fa. Of these HFCs, HFC-4310mee is the most common solvent cleaner replacement. HFC-365mfc is used as an additive to form solvent blends with HFC-4310mee, helping to reduce the cost of these products (Micro Care, 2002). HFC-245fa is used in the aerosol solvent industry (Honeywell, 2003). Heptafluorocyclopentane is another HFC that could be used, although it is not yet used in significant amounts. Certain solvent applications, particularly precision cleaning end-uses, will continue to use HCFCs, especially HCFC-225ca/cb (until the HCFC phaseout takes place), and to a much lesser extent, PFCs and perfluoropolyethers (PFPEs).

This report analyzes three solvent end-uses: metal, precision, and electronics cleaning. Metal cleaning involves the removal of contaminants such as oils, greases, and particulate matter from metal surfaces during the production of metal parts and the maintenance and repair of equipment and machinery. Electronics cleaning, or defluxing, consists mainly of removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces and is characterized by products that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges (UNEP, 1999a). Examples of applications and products requiring precision cleaning include disk drives, gyroscopes, medical devices, and optical components. Based on current understanding of market trends, HFC emissions from the precision and electronics cleaning end-uses dominate the GWP-weighted emissions from the solvents sector. The metal cleaning

¹ Parties to the *Montreal Protocol on Substances that Deplete the Ozone Layer* (Montreal Protocol) agreed to phase out consumption of all ODSs, including those used as solvents. In developed countries, the solvent industry has phased out its use of Class I ODSs (in particular CFCs and 1,1,1-trichloroethane). Developing countries are scheduled to phase out these substances between 2008 and 2010.

² 7,400 is the GWP of perfluorohexane (C₆F₁₄), and is used in this report for estimating purposes as the GWP for PFC/PFPEs.

Table 3-1: General Overview of Solvent Technologies Used Globally

Solvent Classes	Metal	Electronics	Precision
Chlorinated solvents	X	X	X
HCFC solvents (HCFC-225 ca/cb and HCFC-141b)		X	X
HFC solvents (primarily HFC-4310mee)		X	X
PFC solvents		X	X
Hydrofluoroether (HFE) solvents		X	X
Hydrocarbons	X	X	X
Alcohol solvents	X	X	X
Brominated solvents	X	X	X
Methyl siloxanes	X	X	X
Alternative Cleaning Technologies			
Aqueous cleaning	X	X	X
Semiaqueous cleaning	X	X	X
No-clean processes	X	X ^a	

^a For electronics cleaning, no-clean processes include low-solids flux or paste and inert gas soldering.

end-use has primarily transitioned away from ODSs directly into alternatives or processes that do not use high-GWP chemicals.

IV.3.2 Baseline Emissions Estimates

IV.3.2.1 Emissions Estimating Methodology

Description of Methodology

Specific information on how the model calculates solvent emissions is described below.

The USEPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes in the United States, including HFCs and PFCs. Emissions baselines from non-U.S. countries were derived using country-specific ODS consumption estimates as reported under the Montreal Protocol, in conjunction with Vintaging Model output for each ODS-consuming end-use sector. For sectors where detailed information was available, these data were incorporated into country-specific versions of the Vintaging Model to customize emission estimates. In the absence of country-level data, these preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in (1) economic growth, (2) rates of ODS phaseout, and (3) the distribution of ODS use across end-uses in each region or country.

Emissions Equations

Generally, the emissions model assumes that some portion of used solvent remains in the liquid phase and is not emitted as gas. Thus, emissions are considered incomplete and are set as a fraction of the amount of solvent consumed in a year. For solvent applications, a fixed percentage of the new chemical used in equipment is assumed to be emitted in that year, with the remainder of the used solvent reused

or disposed of without being released to the atmosphere. The following equation calculates emissions from solvent applications:

$$E_j = L * Qc_j \quad (3.1)$$

where

- E_j = Total emissions of a specific chemical in a given year j from use in solvent applications, by weight.
- L = The percentage of the total chemical that is lost to the atmosphere, assumed to be 90 percent.
- Qc_j = Total quantity of a specific chemical sold for use in solvent applications in the given year j , by weight.
- j = Year of emissions.

Many solvent users have added emissions control features to their equipment, resulting in lower solvent consumption. Eventually, almost all of the solvent consumed in a given year is emitted, because the solvent is continuously reused through a distilling and cleaning process or through recycling, while a small amount of solvent is disposed with the sludge that remains. The model used for this analysis assumes that 90 percent of the solvent consumed annually is emitted to the atmosphere.

Regional Variations and Adjustments

The following adjustment factor assumptions, specific to the solvent sector, were used to customize the global emissions estimating methodology, described above, for solvents:

- PFC/PFPE solvents were assumed to be used in countries with significant annual output from the electronics industry. Global PFC usage for solvent cleaning was geographically distributed using the semiconductor industry as a proxy; specifically, data on the share of world silicon wafer starts per month (8-inch equivalent) (SEMI International, 2003) were used. PFC/PFPE solvent use was assumed to be discontinued by 2010 in the United States and by 2015 in other countries.
- Emissions in EU-15 countries were assumed to equal only 80 percent of the preliminary estimate to reflect that NIK technology has taken a more significant market share in European countries (ECCP, 2001). Consequently, the resulting EU emissions estimate was reduced by 20 percent.
- A 50-percent adjustment factor was applied to countries with CEITs, European countries that are not members of the EU-15, and developing (non-Annex I) countries. For these countries, the primary barriers to the transition from ODS solvents to fluorinated solvents has been the high cost of HFC-4310mee and the lack of domestic production (UNEP, 1999a; UNEP, 1999b).

IV.3.2.2 Baseline Emissions

Table 3-2 presents total HFC, PFC, and HFE emissions estimates in MtCO₂eq for the solvent sector. In the United States, HFC-4310mee is responsible for the majority of the country's projected ODS substitute solvent emissions, whereas PFC/PFPE emissions are assumed to decline linearly until they are discontinued completely in 2010. U.S. emissions reflect the continued decline of PFC/PFPE consumption as a result of restrictions enforced by the USEPA's Significant New Alternatives Policy Program, which limits PFC and PFPE use to only those applications where these solvents have been deemed necessary to meet performance or safety requirements. U.S. solvent end-users that have historically used PFC/PFPEs are turning to other solvents, including HFC-4310mee.

Table 3-2: Total Baseline HFC, PFC, and HFE Emissions Estimates from Solvents (MtCO₂eq)

Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	10.0	5.4	4.1
Australia/New Zealand	0.2	0.1	0.1
Brazil	0.0	0.1	0.1
China	4.0	1.4	0.1
Eastern Europe	0.1	0.0	0.0
EU-15	3.7	2.1	0.9
India	0.0	0.0	0.0
Japan	3.5	1.4	0.9
Mexico	0.0	0.0	0.0
Non-OECD Annex I	0.0	0.0	0.0
OECD	11.6	5.9	4.1
Russian Federation	0.0	0.0	0.0
South & SE Asia	2.3	0.8	0.2
United States	2.4	1.7	2.0
World Total	16.4	7.7	4.5

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Similarly, some PFC use for precision and electronics cleaning in countries outside the United States was assumed to decline linearly until use is discontinued completely in 2015. Global PFC use for solvent cleaning, as provided by industry expert opinion, was apportioned to non-U.S. countries using the global distribution of the semiconductor market as a proxy for circuit board cleaning, a predominant electronics cleaning end-use (3M Performance Materials, 2004; DuPont FluoroProducts, 2004; SEMI International, 2003).

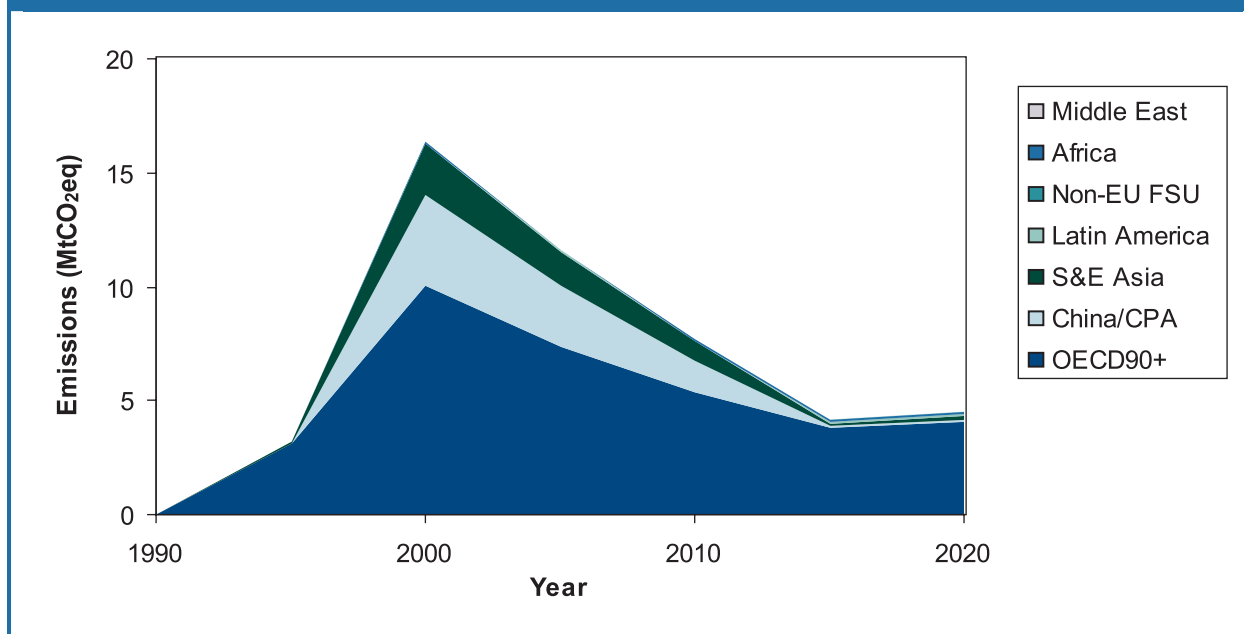
Figure 3-1 displays total HFC, PFC, and HFE emission estimates for the solvent sector by region from 1990 to 2020.

IV.3.3 Cost of HFC, HFE, and PFC Emissions Reductions for Solvents

This section presents a cost analysis for achieving HFC, HFE, and PFC emissions reductions from the emissions baselines presented in Table 3-2 above. All cost analyses for the solvent emissions reduction options assume a 10-year project lifetime. Each abatement option is described below.

IV.3.3.1 Description and Cost Analysis of Abatement Options

Some HFC, HFE, and PFC emissions from the solvent sector can be eliminated or mitigated through several technologies and practices. Emissions and use of these compounds can be reduced by retrofitting equipment and improving containment of the solvents, introducing carbon adsorption technologies, and replacing outdated equipment with more modern technologies. Additionally, NIK technologies and processes already used in many solvent markets worldwide employ semiaqueous, aqueous, or no-clean methods in place of solvents. Ongoing research continues to identify low-GWP alternatives, including low-GWP HFCs and HFEs that could replace high-GWP PFCs and HFCs. Some alternative solvent cleaning approaches use other organic solvents, including chlorinated solvents, alcohols, petroleum distillates, and aliphatic solvents.

Figure 3-1: Total Baseline HFC, PFC, and HFE Emissions Estimates from Solvents (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union; OECD = Organisation for Economic Co-operation and Development.

Flammable organic solvent alternatives, such as ketones, ethers, and alcohols, can also potentially replace HFCs, HFEs, and PFCs. Because these alternatives are fairly aggressive and would have different materials compatibility issues than the fluorinated solvents, and because limited technical and cost information is available on fire suppression equipment, explosion-proof wiring, and other workplace controls, these additional alternatives are not addressed further in this analysis.

Three potential mitigation options are identified and analyzed in this report:

- conversion to HFE solvents,
- improved equipment and cleaning processes using existing solvents (retrofit), and
- aqueous and semiaqueous NIK replacement alternatives.

The remainder of Section IV.3.3 describes each of these options in detail and provides a discussion of associated cost and emissions reduction estimates. A detailed description of the cost and emissions reduction analysis for each option can be found in the Appendix G for this chapter.

Conversion to HFE Solvents

HFC and PFC solvents can be replaced by alternative organic solvents with lower GWPs, which are making headway in the market. These alternative solvents include low-GWP HFCs and HFEs, hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, and non-ODS chlorinated solvents. For the purpose of this analysis, commercially available HFE-7100 and HFE-7200 are used as proxies for the alternative solvent abatement option because they display material compatibility properties similar to HFCs and PFCs, a prime factor that has led to their current success in the market. Specifically, HFEs have replaced PFCs, CFC-113, 1,1,1-trichloroethane, HFCs, and HCFCs in certain precision cleaning operations. Many solvent users have successfully transitioned from PFC solvents to HFC-4310mee and HFEs in cleaning applications such as computer disk lubrication, particulate cleaning,

and cleaning of electronic assemblies after soldering. HFEs and azeotropes of HFEs are also viable replacements for HFC-4310mee in certain precision and electronics cleaning operations.

Because PFCs are specific to a small portion of the global solvent market, and because they are likely to be more expensive than HFCs, costs for this analysis are calculated based on a transition from HFC-4310mee to HFEs, rather than from PFCs to HFEs. Additionally, many users are switching from PFCs to HFC-4310mee. Since this transition is assumed to occur in the baseline, the transition is not quantified as an option for further reductions. Therefore, PFC solvent users that switch directly to HFEs may experience a cost savings compared with HFC solvent users switching to HFEs.

For the purpose of this analysis, the 100-year GWP of alternative solvents reflects the market presence of two HFEs. HFE-7100, which has a GWP of 390, is assumed to represent 75 percent of the market, and HFE-7200, which has a GWP of 55, is assumed to represent the remaining 25 percent. The GWP of the solvent being replaced, HFC-4310mee, is 1,300.³ Because of the lower average GWP, this option has a reduction efficiency of 76.4 percent (i.e., the difference of the GWP of HFC-4310mee and the weighted average of the HFE GWPs, divided by the GWP of HFC-4310mee). This analysis assumes that the technical applicability⁴ of this option is 81 percent of total solvent emissions for each region in 2005, dropping to 79 percent from 2010 through 2020 (Table 3-4).

HFE solvents are gaining acceptance in U.S. industry because of their availability, safety, and effectiveness (Salerno, 2001); however, some uncertainty exists regarding the likelihood and ease with which HFC-4310mee users will convert to an HFE-alternative solvent because of application-specific requirements (UNEP, 1999b). The incremental maximum market penetration of this option in the United States is assumed to increase from 10 percent in 2005 to 60 percent in 2020, as shown in Table 3-4.

For all other countries, the incremental maximum market penetration is assumed to increase from 5 percent in 2005 to 25 percent in 2020, representing a slower adoption of this option and less reliance on the use of fluorinated compounds compared with the assumed scenario for the United States (see Table 3-4). This assumption is based on current market data, which indicates that HFE solvents are available and being used in the same regions where HFC solvents are being used (3M Performance Materials, 2003).

Improved Equipment and Cleaning Processes Using Existing Solvents (Retrofit)

HFCs, HFEs, and PFCs are more expensive than historically used solvents such as CFC-113 and HCFC-141b. Attempts to reduce emissions, and hence save costs, have led to significant improvements in degreasing, defluxing, and other cleaning equipment containment technologies. Engineering control changes (e.g., increased freeboard height, installation of freeboard chillers, and use of automatic hoists), improved containment, and implementation of other abatement technologies can reduce emissions of HFCs, HFEs, and PFCs used in solvent cleaning (UNEP, 1999a; ICF Consulting, 1992). For example, some cleaning equipment that uses HFC solvents is being retrofitted with higher freeboard height and low-temperature secondary cooling coils. It is also possible to keep emissions at a minimum by using good

³ Although the GWP value for HFC-4310mee was taken from the *IPCC Second Assessment Report* (1996), the report did not provide GWP values for either HFE. Consequently, this analysis uses the GWP values listed in the *IPCC Third Assessment Report* (2001) for both HFEs. The GWPs of HFEs are still being studied; for instance, some analyses show the GWP of HFE-7100 to be approximately 300 (3M Performance Materials, 2003).

⁴ In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied. Because HFEs can be substituted for HFCs and PFCs, HFEs are technically applicable to all HFC and PFC solvent emissions, but they are not technically applicable to HFE baseline emissions. Other factors will affect the application of HFCs and PFCs, and the market penetration assumed in this analysis.

handling practices, such as reducing systems' solvent drag-out losses by keeping the workload in the vapor zone long enough to drain and dry any entrapped or remaining solvent (UNEP, 1999a; Petroferm, 2000). One can also minimize evaporative losses by improving the design of solvent bath enclosures and vapor recovery condensing systems (March Consulting Group, 1998 and 1999).

As shown in Table 3-3, retrofitting a vapor degreaser with an open-top area of 13 square feet, combined with proper operation and maintenance, can reduce solvent emissions by as much as 46 to 70 percent, depending on the specific retrofit methods chosen (Durkee, 1997). For example, installing a freeboard refrigeration device, sometimes referred to as a chiller (i.e., a set of secondary coils mounted in the freeboard), and maintaining a freeboard ratio of 1.0 to minimize diffusional solvent losses, can reduce emissions by 46 percent, while installing heating coils to produce superheated vapor along with installing a chiller can reduce emissions by 70 percent. For the purpose of this analysis, the reduction efficiency of the retrofit option is assumed to equal 70 percent, which can be achieved at a one-time cost of \$16,800 (see Table 3-3).

Table 3-3: Retrofit Techniques for Batch Vapor Cleaning Machine (Less than 13 Square Feet)

Retrofit Technique	Reduction Efficiency (%)	One-Time Cost (2000\$)
Freeboard ratio of 1.0, freeboard refrigeration device	46.0%	\$11,200
Working mode cover, freeboard refrigeration device	64.0%	\$15,800
Superheated vapor, freeboard refrigeration device	70.0%	\$16,800

Source: Durkee, 1997.

Retrofits to vapor degreasing machines larger than 13 square feet cost more but can achieve emissions reduction efficiencies as high as 85 percent. Furthermore, for larger operations where there is more than one vapor degreaser, retrofit methods, such as installing a carbon adsorber, can be implemented to capture solvent vapor from the air for the entire facility. The reduction efficiency of a carbon adsorber combined with the installation of heating coils and chillers has been estimated at 88 percent for larger (i.e., greater than 13 square feet) vapor degreasers (Durkee, 1997).

In the United States, many enterprises have bought new equipment or retrofitted aging equipment into compliance with the National Emissions Standard for Hazardous Air Pollutants (NESHAP), which limits emissions from degreasers using traditional chlorinated solvents such as trichloroethylene. Fluorinated solvents such as HFCs are not covered by this regulation; nonetheless, a number of companies using HFCs and other nonchlorinated solvents have adopted NESHAP-compliant solvent cleaning machines because of the associated economic, occupational, and environmental benefits (Durkee, 1997). Consequently, end-users in the United States are not expected to benefit from this option in the future. Thus, this analysis assumes that the incremental maximum market penetration will drop from 5 percent in 2005, to zero in 2010 through 2020 (i.e., by 2010 and beyond, the solvent equipment in use will either already be retrofitted or will not require retrofitting, and the resulting lower emissions are already incorporated into the baseline). The resulting maximum market penetrations are shown in Table 3-4.

Likewise, many European countries have imposed stringent environmental and safety regulations that require the lowest level of emissions attainable by solvent degreasing equipment. Retrofit techniques were either already implemented or simply not required if the user had purchased new emission-tight vapor degreasers. Therefore, for non-U.S. Annex I countries, the maximum market penetration for this option is also assumed to be 5 percent in 2005, dropping to zero by 2010.

This analysis assumes that most solvent users in non-Annex I (i.e., developing) countries may consider the equipment retrofit option, because updating their equipment may be preferred over investing in entirely new units. Consequently, this region is assumed to adopt these techniques slowly, such that 5 percent of the market will have adopted this option by 2005. Adoption is assumed to increase at a slow, steady rate to 15 percent in 2020 (see Table 3-4).

Aqueous and Semiaqueous NIK Replacement Alternatives

In addition to the emissions reduction approaches that use a combination of improved equipment and cleaning practices, NIK technology processes and solvent replacements can be used to substitute for PFC-, HFC-, and HFE-containing systems. In the aqueous process, a water-based cleaning solution is used as the primary solvent and is usually combined with a detergent to remove contaminants. In the semiaqueous process, the cleaning solution is an organic solvent that is blended with a surfactant, making it water soluble. An example of a solvent/surfactant blend is a terpene/water combination blended with glycol ethers (UNEP, 1999a). The reduction efficiency of NIK abatement options is assumed to be 100 percent because the HFC or PFC solvent is completely replaced by water and an organic solvent, combinations of which have low to no GWP.

Many electronics, metal, and precision cleaning end-users have already switched to aqueous and semiaqueous NIK cleaning methods. Both NIK processes have proven very successful for large-scale metal cleaning, where equipment and wastewater treatment costs are of less concern because of the large volumes processed (UNEP, 1999a). Aqueous cleaning technologies have been available and widely used for over 25 years and have replaced many electronics cleaning solvent systems in developed countries (Chaneski, 1997; UNEP, 1999a). Semiaqueous cleaning has also been available for years but has lost much of its initial promise in many developed nations for the cleaning of electronic assemblies because of the additional complexity and subsequent expense associated with the cleaning process, which includes more steps than aqueous cleaning (UNEP, 1999a).

Because the NIK options are applicable to both the electronic and precision cleaning end-uses, the NIK options are assumed to be applicable to 100 percent of high-GWP solvent emissions, resulting in a technical applicability of 100 percent for all regions (see Table 3-4). The assumed market penetration, however, is lower, as explained below.

Technical limitations of NIK technologies arising from issues such as substrate corrosion or inadequate performance for applications with complex parts can lead to reduced market acceptability. The U.S. incremental maximum market penetrations for these options are assumed to be smaller than in other regions, to reflect the belief that the U.S. market will likely prefer fluorinated solvents such as HFCs and HFEs (see Table 3-4). The market penetrations are also assumed to be smaller because most operations that can use aqueous and semiaqueous technologies are doing so already. For non-U.S. Annex I and non-Annex I regions, the maximum market penetrations of these two NIK options are assumed to be similar to each other from 2005 to 2020. NIK alternatives are currently gaining market share in European countries, a trend that is assumed to continue for this region (ECCP, 2001).

Some developing countries are also assumed to prefer NIK technologies because of their perceived low costs. Aqueous cleaning is popular in China, for example, because of the small cost per kilogram of the nonfluorinated cleaning chemicals used, despite newly introduced costs such as wastewater treatment. Conversely, the availability of water, the costs associated with energy to dry the product, and local wastewater treatment regulations can discourage companies in developing regions of the world from considering this option (UNEP, 2003). For all regions, the semiaqueous option is assumed to have slightly smaller market penetrations than the aqueous cleaning option.

IV.3.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 3-4 summarizes the technical applicability and the maximum market penetration of the solvent options presented in the discussions above. By 2020, it is assumed that the NIK replacement option can be applied to 15 percent of the baseline solvent emissions in the United States, 30 percent of the baseline solvent emissions in the Annex I countries, and 30 percent of the baseline solvent emissions in non-Annex I countries. By 2020, the retrofit option is assumed to be viable only in non-Annex I countries. In addition, the conversion to HFE solvents option can be applied to the baseline HFC and PFC emissions, as shown below.

Table 3-4: Technical Applicability and Incremental Maximum Market Penetration of Solvent Options (Percent)^a

Option	Technical Applicability (All Years) ^b			Market Penetration											
	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I
				2005			2010			2015			2020		
Retrofit	100%	100%	100%	5%	5%	5%	0%	0%	8%	0%	0%	12%	0%	0%	15%
Conversion to HFE solvents	79–81%	79–81%	79–81%	10%	5%	5%	30%	10%	10%	45%	15%	15%	60%	25%	25%
NIK replacements	100%	100%	100%	4%	8%	8%	8%	15%	15%	12%	23%	23%	15%	30%	30%
Semiaqueous	100%	100%	100%	1%	3%	3%	3%	5%	5%	4%	8%	8%	5%	10%	10%
Aqueous	100%	100%	100%	3%	5%	5%	5%	10%	10%	8%	15%	15%	10%	20%	20%

^a Assumed maximum market penetration of options is presented as a percentage of total sector emissions for which the options are technically applicable. The baseline market penetration is assumed to be zero to assess the emissions reductions possible due to increased use of each option.

^b The percentage of total emissions represented by HFEs varies by year. The technical applicability is 81 percent in 2005, and 79 percent in 2010 through 2020.

To calculate the percentage of emissions reductions off the total solvent baseline for each abatement option, the technical applicability (Table 3-4) is multiplied by the market penetration value (Table 3-4) and by the reduction efficiency of the option. For example, to determine the percentage reduction off the 2020 baseline for the “conversion to HFE solvents” option in the United States, the following calculation is performed:

$$\text{Technical applicability} \times \text{Market penetration in 2020} \times \text{Reduction efficiency} = \\ 79.0\% \times 60.0\% \times 76.4\% \approx 36.2\%$$

Thus, using the assumptions in this analysis, converting to an HFE solvent could reduce approximately 36 percent of the U.S. emissions baseline in 2020. This figure, along with the other emissions reduction potentials, is shown in Table 3-5.

Table 3-6 presents a summary of the cost assumptions used for the solvent options presented in the discussions above.

Table 3-5: Emissions Reductions Off the Total Solvent Baseline (Percent)

	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I	United States	Non-U.S. Annex I	Non-Annex I
Option	2005			2010			2015			2020		
Retrofit	3.5%	3.5%	3.5%	0.0%	0.0%	5.6%	0.0%	0.0%	8.4%	0.0%	0.0%	10.5%
Conversion to HFE solvents	6.2%	3.1%	3.1%	18.1%	6.0%	6.0%	27.2%	9.1%	9.1%	36.2%	15.1%	15.1%
NIK replacements	3.8%	7.5%	7.5%	7.5%	15.0%	15.0%	11.3%	22.5%	22.5%	15.0%	30.0%	30.0%
Semiaqueous	1.3%	2.5%	2.5%	2.5%	5.0%	5.0%	3.8%	7.5%	7.5%	5.0%	10.0%	10.0%
Aqueous	2.5%	5.0%	5.0%	5.0%	10.0%	10.0%	7.5%	15.0%	15.0%	10.0%	20.0%	20.0%

Table 3-6: Summary of Abatement Option Cost Assumptions

Option	Time Horizon (Years)	Unit of Costs	Base One-Time Cost (2000\$)	Base Annual Cost (2000\$)	Base Annual Savings (2000\$)	Net Annual Costs (2000\$/yr)
Retrofit	10	Per degreaser with an open-top area 13 ft ²	\$16,800	\$0	\$233,300	−\$233,300
NIK aqueous	10	Per standard degreaser unit	\$80,000	\$0	\$0	\$0
NIK semiaqueous	10	Per standard degreaser unit	\$10,000	\$0	\$0	\$0
HFC to HFE	10	Per kilogram of solvent	\$0	\$0	\$0	\$0

IV.3.4 Results

IV.3.4.1 Data Tables and Graphs

Tables 3-7 and 3-8 provide a summary of the potential emissions reduction opportunities at associated breakeven costs in 15-dollar increments at a 10 percent discount rate (DR) and 40 percent tax rate (TR). As shown, in 2010 and 2020, emissions reduction opportunities become available for regions such as Annex I and OECD at the lowest breakeven cost of \$0/tCO₂eq. For regions such as Mexico and the Russian Federation, emissions reduction opportunities are not available because emissions from the solvent sector are so minute for these regions. A world total emissions reduction of 1.83 MtCO₂eq is projected by 2010 and 2.20 MtCO₂eq by 2020, both at a breakeven cost of \$15/tCO₂eq.

Table 3-9 presents the costs, in 2000\$, to reduce 1 MtCO₂eq for a discount rate scenario of 10 percent and a tax rate of 40 percent. The results are ordered by increasing costs per tCO₂eq. Also presented are the emissions reduced by the option, in MtCO₂eq and percentage of the solvents baseline, and cumulative totals of these two figures.

Table 3-7: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Solvents at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.01	0.01	0.01	0.01	0.01
Annex I	0.53	1.21	1.21	1.21	1.21	1.21
Australia/New Zealand	0.00	0.02	0.02	0.02	0.02	0.02
Brazil	0.01	0.01	0.01	0.01	0.01	0.01
China	0.16	0.37	0.37	0.37	0.37	0.37
Eastern Europe	0.00	0.01	0.01	0.01	0.01	0.01
EU-15	0.13	0.45	0.45	0.45	0.45	0.45
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.08	0.29	0.29	0.29	0.29	0.29
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	0.00	0.00	0.00	0.00	0.00
OECD	0.59	1.36	1.36	1.36	1.36	1.36
Russian Federation	0.00	0.00	0.00	0.00	0.00	0.00
South & SE Asia	0.03	0.07	0.07	0.07	0.07	0.07
United States	0.30	0.43	0.43	0.43	0.43	0.43
World Total	0.80	1.83	1.83	1.83	1.83	1.83

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 3-8: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Solvents at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

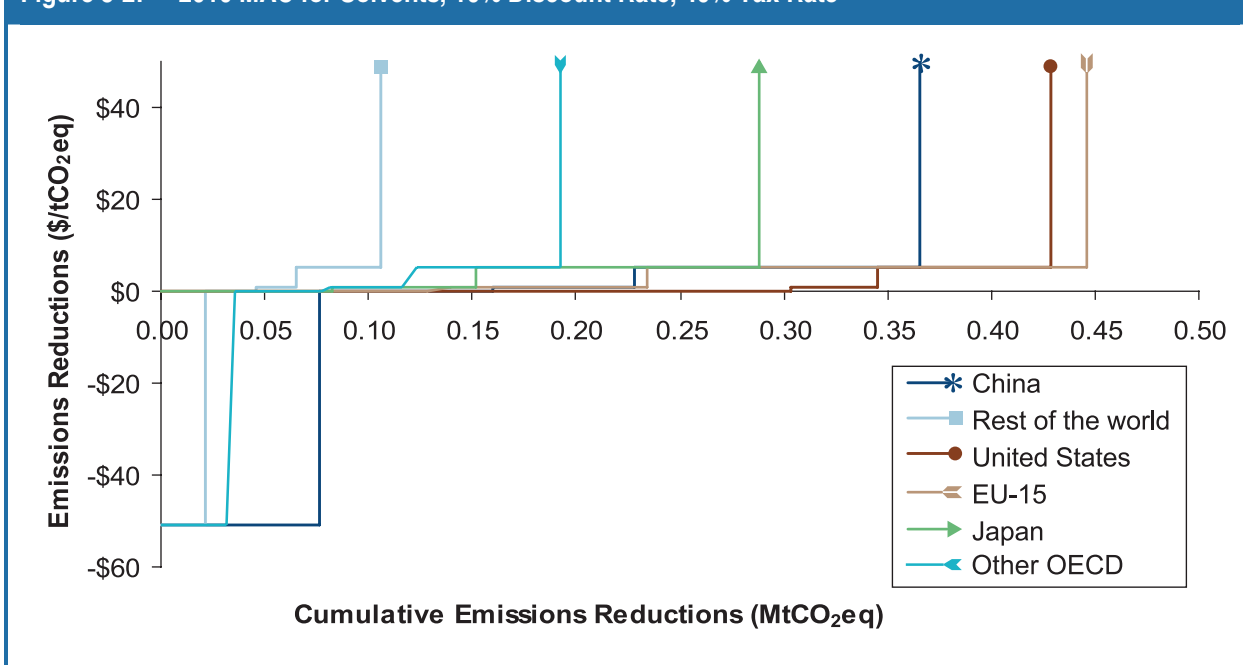
Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.01	0.02	0.02	0.02	0.02	0.02
Annex I	1.05	1.96	1.96	1.96	1.96	1.96
Australia/New Zealand	0.01	0.04	0.04	0.04	0.04	0.04
Brazil	0.02	0.04	0.04	0.04	0.04	0.04
China	0.03	0.06	0.06	0.06	0.06	0.06
Eastern Europe	0.00	0.01	0.01	0.01	0.01	0.01
EU-15	0.14	0.40	0.40	0.40	0.40	0.40
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.13	0.40	0.40	0.40	0.40	0.40
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	0.01	0.01	0.01	0.01	0.01
OECD	1.07	2.01	2.01	2.01	2.01	2.01
Russian Federation	0.00	0.00	0.00	0.00	0.00	0.00
South & SE Asia	0.02	0.05	0.05	0.05	0.05	0.05
United States	0.74	1.05	1.05	1.05	1.05	1.05
World Total	1.16	2.20	2.20	2.20	2.20	2.20

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

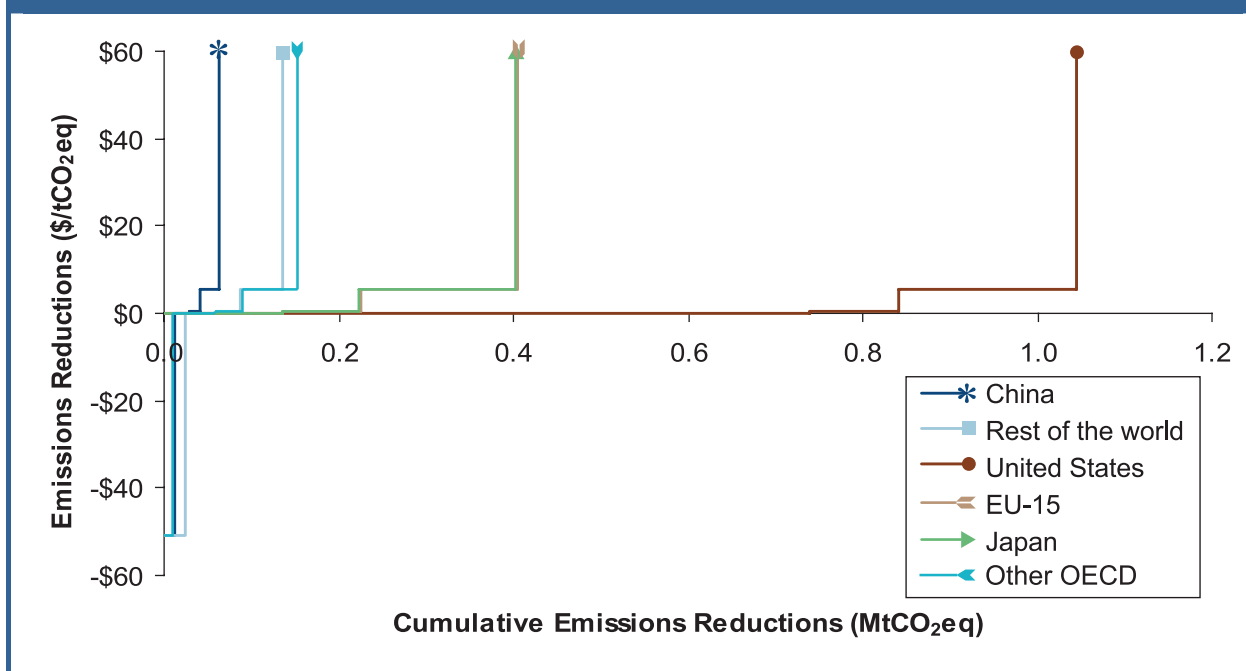
Table 3-9: World Breakeven Costs and Emissions Reductions in 2020 for Solvents

Reduction Option	Cost (2000\$/tCO ₂ eq) 10% DR, 40% TR	Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Cumulative Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
Retrofit	-\$50.75	0.0454	1.0%	0.05	1.0%
HFC to HFE	\$0.00	1.11	24.7%	1.16	25.7%
NIK semiaqueous	\$0.67	0.35	7.7%	1.51	33.4%
NIK aqueous	\$5.36	0.70	15.5%	2.20	48.9%

Figures 3-2 and 3-3 display the solvent international marginal abatement curves (MACs) by region for 2010 and 2020, respectively.

Figure 3-2: 2010 MAC for Solvents, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 3-3: 2020 MAC for Solvents, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.3.4.2 Uncertainties and Limitations

This section focuses on the uncertainties and limitations associated with the cost estimates presented in this analysis. One significant area of uncertainty is how capital costs for these mitigation technologies may vary internationally. The analysis is currently limited by the lack of this specificity on region-specific cost analysis estimates. In addition, the three abatement options identified in this analysis have the following uncertainties.

Conversion to HFE Solvents

Short- and long-term cost savings may occur with this option; yet because of their uncertainty, this analysis conservatively assumes no cost savings.

Improved Equipment and Cleaning Processes Using Existing Solvents (Retrofit)

The analysis does not realize any annual labor costs that may accompany the use of retrofitted equipment. These incurred costs may include training and frequent, mandatory maintenance checks.

Aqueous and Semiaqueous NIK Replacement Alternatives

The major uncertainties regarding this option are the annual costs and cost savings. Because cost savings, which may offset increased operating costs, are not quantified for this analysis, this analysis does not assume annual costs or cost savings for this option.

IV.3.5 Summary

Baseline global HFC, HFE, and PFC emissions from solvents are estimated to decline from 16.4 to 4.5 MtCO₂eq between 2000 and 2020. In 2020, Annex I countries are assumed to account for approximately 90 percent of global emissions, with U.S. emissions assumed to account for half of emissions from Annex I

countries (Table 3-2). Projected growth in emissions (between 2010 and 2020) is expected to occur only in the United States, from 1.7 MtCO₂eq in 2010 to 2.0 MtCO₂eq in 2020.

This analysis considers three emissions mitigation options for solvent use: (1) adoption of alternative, (HFE-7100 or HFE-7200) partially fluorinated solvents, (2) improved system design through retrofitting solvent processes, and (3) conversion to NIK (aqueous and semiaqueous replacements). The costs and emissions reduction benefits of each option were compared in each region (Tables 3-7 and 3-8). Globally, retrofitting represents the most cost-effective option for reducing HFC, HFE, and PFC emissions from the solvent sector, with a cost savings of \$50.75 per tCO₂eq at a 10 percent discount rate and 40 percent tax rate. Converting to an HFE solvent is a cost-neutral option for all regions. By 2020, 2.20 MtCO₂eq, or 49 percent of global baseline emissions from solvents, can be reduced at a cost under \$10 per tCO₂eq.

For all three options, costs per tCO₂eq for each region are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Actual costs for abatement options for specific countries may vary and subsequently affect these estimates. Additional research is required to determine actual variability in costs across regions.

IV.3.6 References

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IV.4 HFC Emissions from Foams

IV.4.1 Introduction

Various HFCs are currently being used as blowing agents during the manufacture of foams. These high-GWP gases are substitutes for ODSs that were historically the primary blowing agents in the foams industry. Parties to the *Montreal Protocol on Substances that Deplete the Ozone Layer* are phasing out CFCs, and many are using HCFCs as interim substitutes. Developed and developing countries are at different phases of replacing CFCs with alternatives. Developed regions, such as the United States and EU-15, have banned the sale and distribution of some foam products manufactured with HCFCs and have begun transitioning to HFC use in foams where HCs and other alternatives are not already used. For example, Denmark, Austria, Finland, and Sweden phased out the use of HCFCs for foam blowing on January 1, 2002, while in the United States, HCFC-141b has been phased out but HCFC-22 is still being used.

Developing countries have only recently begun transitioning from CFC-11 to HCFCs and other alternatives. The rate of conversion to HFCs may be limited by the current availability of other ODS substitutes and by technical barriers and cost. For example, the main blowing agent alternatives for CFC-11 in rigid polyurethane (PU) insulating foams are HCs, such as pentanes, and HCFCs. Applying alternative (i.e., HFC) technologies may require the use of higher-density foam, which would result in incremental operating cost increases CO₂.

The most commonly used HFC blowing agents are HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc in combination with HFC-227ea. These blowing agents can be released into the atmosphere during the foam manufacturing process, during on-site foam application, while foams are in use, and when foams are discarded. These agents have 100-year GWPs of 1,300, 140, 950, and 890 in combination with 2900, respectively, and have replaced historically used ODS blowing agents, including CFCs and HCFCs. Foams studied in this analysis include the following:

- PU appliance foams found in various commercial and domestic refrigerators, vending machines, freezers, water heaters, picnic boxes, flasks, thermoware, and refrigerated containers (reefers). PU foam is the main insulation material used in refrigerators and freezers. PU foam must provide continuous and effective insulation to ensure the quality of the product stored inside; therefore, insulation properties must be maintained in order to preserve the performance of the appliance. Basic performance requirements of some appliances are universal (e.g., refrigerators and freezers keep food cold and water heaters keep water warm); however, some markets have specific requirements such as energy consumption limits.
- PU spray foams are found in roofing insulation, wall insulation, and for insulation of various tank pipe and vessel applications. PU spray foam is used in both residential and commercial buildings as well as refrigerated transport. The main application in this category is spray roofing insulation.
- PU continuous and discontinuous panel foam is used for insulation of cold storage, entrance and garage doors, insulated trucks, etc.
- PU one-component foams are used for insulation around windows and doors, framing around pipes, cable holes, jointing insulating panels, and certain roof components. PU one-component foam is a preferred insulation method for portable and “easy to administer” applications.

- Extruded polystyrene (XPS) boardstock foam is used mainly for thermal insulation purposes in buildings. Its primary uses include basement walls, exterior walls, cavity walls, and roofing. Its resistance to water absorption makes it a prime selection for “below-grade” applications. Some XPS boardstock foam types are used in protection of roads or airport runways against frost (“geofoam applications”).

IV.4.2 Baseline Emissions Estimates

IV.4.2.1 Emissions Estimating Methodology

The USEPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODSs and ODS substitutes in the United States, including HFCs and PFCs. Emissions baselines from non-U.S. countries were derived using country-specific ODS consumption estimates, as reported under the Montreal Protocol in conjunction with Vintaging Model output for each ODS-consuming end-use. These data were incorporated into country-specific versions of the Vintaging Model to customize emissions estimates. In the absence of country-level data, these preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and PFCs follows the same general substitution patterns internationally as the patterns observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios based on relative differences in economic growth, rates of ODS phaseout, and the distribution of ODS use across end-uses in each region or country.

Emissions Equations

Foams are given emissions profiles depending on the foam type (open cell or closed cell). Open-cell foams are assumed to be 100 percent emissive in the year of manufacture, as described in Equation (4.1) below. Closed-cell foams are assumed to emit a portion of their total HFC or PFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion postdisposal, as described in Equations (4.2) through (4.6), below.¹

Open-Cell Foam

$$E_j = Qc_j \quad (4.1)$$

where

- E_j = Emissions. Total emissions of a specific chemical in year j used for open-cell foam blowing, by weight.
- Q_c = Quantity of chemical. Total amount of a specific chemical used for open-cell foam blowing in a given year, by weight.
- j = Year of emission.

¹ Emissions from foams may vary because of handling and disposal of the foam; shredding of foams may increase emissions, while landfilling of foams may abate some emissions (Scheutz and Kjeldsen, 2002; Scheutz and Kjeldsen, 2003). Average annual emissions are assumed in the model, which may not fully account for the range of foam handling and disposal practices.

Closed-Cell Foam

Emissions from foams occur at many different stages, including manufacturing, lifetime, disposal, and postdisposal.

Manufacturing emissions occur in the year of foam manufacture, and are calculated as presented in Equation (4.2).

$$Em_j = lm \times Qc_j \quad (4.2)$$

where

- Em_j = Emissions from manufacturing. Total emissions of a specific chemical in year j due to manufacturing losses, by weight.
- lm = Loss rate. Percent of original blowing agent emitted during foam manufacture.
- Qc = Quantity of chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
- j = Year of emission.

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated using Equation (4.3).

$$Eu_j = lu \times \sum Qc_{j-i+1} \text{ for } i = 1 \rightarrow k \quad (4.3)$$

where

- Eu_j = Emissions from lifetime losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
- lu = Leak rate. Percentage of original blowing agent emitted during lifetime use.
- Qc = Quantity of chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
- k = Lifetime. Average lifetime of foam product.
- i = Counter. Runs from 1 to lifetime (k).
- j = Year of emission.

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in Equation (4.4).

$$Ed_j = ld \times Qc_{j-k} \quad (4.4)$$

where

- Ed_j = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.
- ld = Loss rate. Percent of original blowing agent emitted at disposal.
- Qc = Quantity of chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
- k = Lifetime. Average lifetime of foam product.
- j = Year of emission.

Postdisposal emissions occur in the years after the foam is disposed, and are assumed to occur while the disposed foam is in a landfill. Currently, the only foam type assumed to have postdisposal emissions is

polyurethane appliance foam, which is expected to continue to emit for 32 years postdisposal, and is calculated as presented in Equation (4.5).

$$Ep_j = lp \times \sum Qc_{j-m} \text{ for } m = k \rightarrow k + 32 \quad (4.5)$$

where

- Ep_j = Emissions postdisposal. Total postdisposal emissions of a specific chemical in year j , by weight.
- lp = Leak rate. Percent of original blowing agent emitted post disposal.
- Qc = Quantity of chemical. Total amount of a specific chemical used in closed-cell foams in a given year.
- k = Lifetime. Average lifetime of foam product.
- m = Counter. Runs from lifetime (k) to ($k + 32$).
- j = Year of emission.

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in Equation (4.6).

$$E_j = Em_j + Eu_j + Ed_j + Ep_j \quad (4.6)$$

where

- E_j = Total emissions. Total emissions of a specific chemical in year j , by weight.
- Em_j = Emissions from manufacturing losses. Total emissions of a specific chemical in year j due to manufacturing leaks, by weight.
- Eu_j = Emissions from lifetime losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
- Ed_j = Emissions at disposal. Total emissions of a specific chemical in year j due to disposal, by weight.
- Ep_j = Emissions postdisposal. Total postdisposal emissions of a specific chemical in year j , by weight.

The emissions profile for foams estimated by the Vintaging Model is presented in Table 4-1.

Regional Adjustments

Foam sector emissions were estimated by developing Vintaging Model scenarios that were representative of country- or region-specific substitution and consumption patterns. To estimate baseline emissions, current and projected characterizations of international total foams markets were used to create country- or region-specific versions of the Vintaging Model. The market information was obtained from Ashford (2004), based on research conducted on global foam markets. Scenarios were developed for Japan, Europe (both EU-15 and non-EU-15 countries combined), other developed countries (excluding Canada), CEITs, and China. Other non-Annex I countries are assumed not to transition to HFCs during the scope of this analysis. Once the Vintaging Model scenarios had been run, the emissions were disaggregated to a country-specific level based on estimated 1989 CFC consumption for foams developed for this analysis. Emissions estimates were adjusted slightly to account for relative differences in countries' economic growth compared to the United States (USDA, 2002; USEIA, 2001).

Table 4-1: USEPA's Vintaging Model Emissions Profile for Foams' End-Uses

Foams End-Use	Loss at Manufacturing (Percent)	Annual Release Rate (Percent)	Release Lifetime (Years)	Loss at Disposal (Percent)	Total Released (Percent)
Flexible PU	100.0%	0.000%	1	0.00%	100.0%
Polyisocyanurate boardstock	6.0%	1.000%	50	44.00%	100.0%
Rigid PU integral skin	95.0%	2.500%	2	0.00%	100.0%
PU appliance	4.0%	0.250%	20	27.30% ^a	36.3% ^b
PU commercial refrigeration	6.0%	0.250%	15	90.25%	100.0%
PU spray	15.0%	1.500%	56	1.00%	100.0%
One component	100.0%	0.000%	1	0.00%	100.0%
PU slabstock and other	37.5%	0.750%	15	51.25%	100.0%
Phenolic	23.0%	0.875%	32	49.00%	100.0%
Polyolefin	95.0%	2.500%	2	0.00%	100.0%
XPS foam sheet	40.0%	2.000%	25	0.00%	90.0%
XPS boardstock	25.0%	0.750%	50	37.50%	100.0%
Sandwich panel	5.5%	0.500%	50	69.50%	100.0%

^a Estimated as 30 percent of the blowing agent remaining in the foam at the time of disposal (Scheutz and Kjeldsen, 2002).

^b Emissions from disposed of products may continue if not otherwise abated. For HFCs, this analysis assumes 2 percent of the total blowing agent used will continue to be emitted every year after disposal.

Emissions baselines for Canada were derived using country-specific ODS consumption estimates, as reported under the Montreal Protocol, in conjunction with U.S. Vintaging Model output for each ODS-consuming end-use sector. Preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns as observed in the United States.

Newly Manufactured Foam Emissions Versus Existing Foam Emissions

Technology options explored in the foams chapter are only applicable to new (i.e., not existing) foams. Therefore, the technical applicabilities² of the technology options in this sector include only emissions from relevant end-uses that are from newly manufactured foams, which are defined as foams manufactured in 2005 or later.

IV.4.2.2 Baseline Emissions

Table 4-2 provides a summary of baseline HFC emissions for the United States, other Annex I countries, non-Annex I countries³ and other groupings through 2020. Emissions estimates for HFCs from the foam sector are presented in MtCO₂eq. These results are shown also in Figure 4-1.

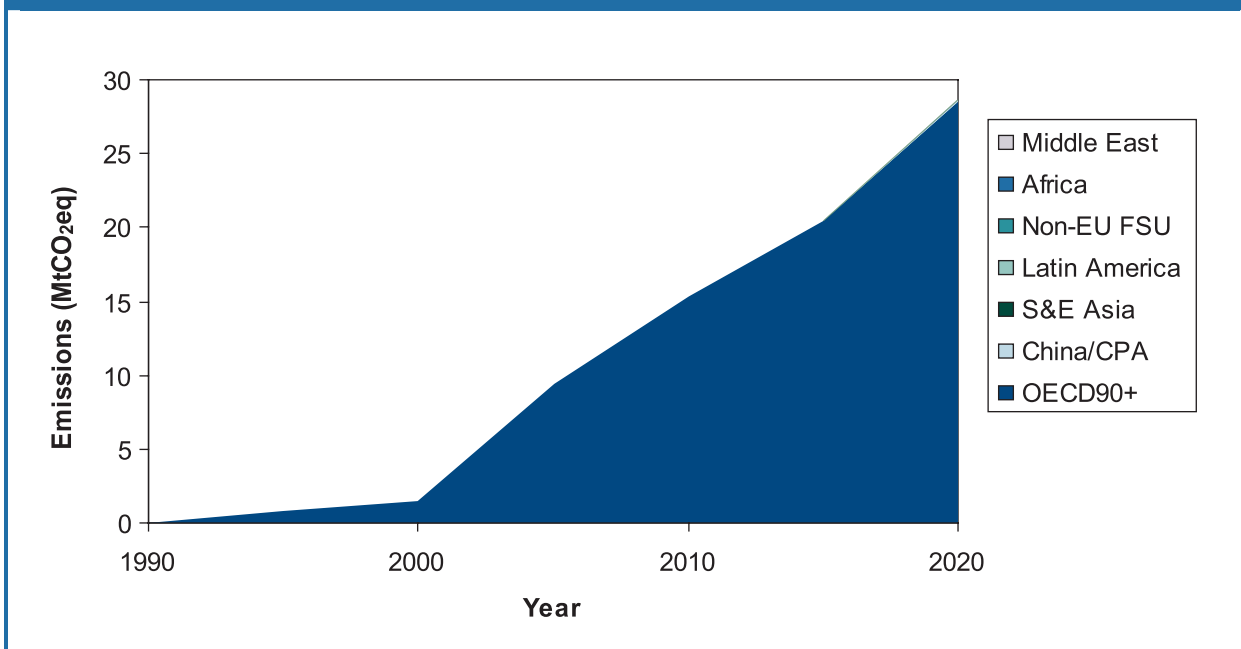
² In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied.

³ This analysis assumes that China is the only non-Annex I country that would transition to HFCs during the scope of this study.

Table 4-2: Baseline Emissions Estimates for Foams (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	1.5	15.4	28.6
Australia/New Zealand	0.0	0.1	0.2
Brazil	0.0	0.0	0.0
China	0.0	0.0	0.1
Eastern Europe	0.0	0.0	0.0
EU-15	1.1	5.9	11.4
India	0.0	0.0	0.0
Japan	0.0	3.3	4.8
Mexico	0.0	0.0	0.0
Non-OECD Annex I	0.0	0.0	0.1
OECD	1.5	15.3	28.5
Russian Federation	0.0	0.0	0.0
South & SE Asia	0.0	0.0	0.0
United States	0.3	5.7	11.3
World Total	1.5	15.4	28.6

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 4-1: Total Baseline Emissions Estimates for Foams (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development; S&E Asia = Southeast Asia.

IV.4.3 Cost of HFC Emissions Reductions from Foams

This section presents a cost analysis of achieving HFC emissions reductions from the emissions baseline presented above.

For chemical replacement options, costs were based on the incremental differences between using the HFC and switching to an HFC alternative. Financial information considered in this analysis includes capital costs, which account for equipment costs to modify existing plants and to maintain production capacity; blowing agent costs, which address the difference between costs and the quantity of the HFC and non-HFC alternative required; foam costs, which address changes in foam density, the amount of fire retardant used, the quantity and type of polyol, etc.; costs associated with profit and productivity; testing, training, or other costs associated with transitioning to non-HFC alternatives; and costs to produce a thicker, denser foam to account for any energy efficiency differences.

In addition, industry has indicated that there will be additional conversion or “learning curve” costs, which are short-term costs incurred from yield, rate, and density penalties associated with conversion uncertainties, as well as technical support costs. Such costs are highly variable and are not addressed in the analysis.

IV.4.3.1 Abatement Options

Specific opportunities to reduce HFC emissions from the foams that were analyzed for this report fall into two basic categories: blowing agent replacement options and end-of-life handling options.

Blowing agent replacement options include the following:

- replacing HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea with HCs in PU continuous and discontinuous panel foam;
- replacing HFC-134a and HFC-152a with HCs in one-component foam;
- replacing HFC-134a and carbon dioxide (CO₂)-based blowing agents with liquid CO₂ (LCD)/alcohol in XPS boardstock foam;
- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water) in PU spray foam;
- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with HCs in PU spray foam;
- replacing HFC-134a with HCs in PU appliance; and
- replacing HFC-245fa and HFC-365mfc/HFC-227ea with HCs in PU appliance foam.

End-of-life handling options include the following:

- PU appliance foam practice: automated process with foam grinding and landfilling and
- PU appliance foam practice: manual process with incineration.

All abatement option cost analyses assume a 25-year project lifetime.

Replacement Options

Each of the replacement options includes the use of non-HFC blowing agents such as HCs, water-blown CO₂, and LCD. These foam technologies are described below. Section IV.4.3.2 gives specific analyses of the costs of applying these alternate blowing agents to particular foam types.

Hydrocarbons

HCs such as propane, butane, isobutane, n-pentane, isopentane, cyclopentane, and isomers of hexane are alternatives to HFCs in foam blowing appliances. HCs are inexpensive and have near-zero direct GWPs, much lower than HFCs. However, key technical issues associated with the use of HCs exist:

- **Flammability.** Factory upgrades that among other things ensure the use of nonsparking equipment and employee training are required when switching to HCs, to meet the necessary safety precautions in manufacturing, storage, handling, transport, and customer use. Examples of upgrades include a dedicated storage tank for the HC, premixers, adapted high-pressure dispensers, suitable molds plus process exhaust, HC detectors, and appropriate classification of electrical equipment. To reduce fire risks, some applications might also require the use of a larger quantity of flame retardants or the use of a more expensive fire retardant.
- **Volatile Organic Compounds (VOCs).** Because HCs contribute to ground-level ozone and smog, they tend to be highly regulated. In many places, including some parts of the United States, HCs cannot be used without emissions controls. Implementation of these controls can lead to significant increases in the costs of conversion.
- **Performance.** Some HCs yield only about 85 percent of the insulating value of HCFC-141b, HFC-245fa, and HFC-365mfc/HFC-227ea. Producing a thicker foam can compensate for this energy efficiency difference, but will increase the cost of production and possible application costs (e.g., longer fasteners for thicker foam board). This option might not be viable in fixed-thickness applications, such as refrigerated trucks, or in applications where an R-value is prescribed by code, such as in PU spray roofing insulation. Other performance considerations include dimensional stability and solubility. Addressing these factors might require a more expensive and more limited polyol formulation.

Costs of converting to HCs and addressing technical considerations can be significant, but vary according to factory-specific needs. HCs can also be used to enhance octane ratings, making them valuable for gasoline use and affecting their cost (Werkema, 2006). In spite of these issues, HCs are currently used in some applications and are being considered in a wide variety of additional applications (UNEP, 1998; Alliance, 2000; Alliance, 2001).

Liquid Carbon Dioxide

The basic principle by which LCD blowing agents operate is the expansion of LCD to a gaseous state. LCD is blended with other foam components under pressure prior to initiating the chemical reaction. When decompressed, the CO₂ expands, resulting in froth foam, which further expands with the additional release of CO₂ from the water/isocyanate resin reaction that forms the PU foam matrix. LCD might require formulation changes to more readily dissolve the CO₂ and to prevent deactivation of PU catalysts. When LCD is introduced at the head, often referred to as third stream, the metering equipment can be quite complicated and, to date, unreliable. Difficulties encountered in using LCD include the limited solubility of the chemical mixture, controlled decompression, and distribution of the unavoidable froth (UNEP, 1998). Foams blown with CO₂ may suffer from lower thermal conductivity, lower dimensional stability, and higher density than HCFC-blown foams. To overcome these limitations, CO₂ can be blended with HCs or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001).

Water-Blown (In Situ) CO₂ (Water)

In this process, CO₂ produced from a chemical reaction between water and polymeric isocyanate is used as a blowing agent. During manufacture, no ODS or high-GWP gases are emitted, and there are limited health and safety risks during processing. However, foams produced using CO₂/water are subject

to the same performance limitations discussed for LCD-blown foams: lower thermal conductivity, lower dimensional stability, and higher density than HCFC- and HFC-blown foams. In some PU foam applications, a major concern when using water-generated or LCD systems is the increased open-cell content, which results in poorer waterproofing performance and poorer waterproofing quality of the final product. Another consideration is that the polymeric isocyanate content must be increased, which cannot be accommodated by some PU spray foam equipment. To overcome these limitations, CO₂ can be blended with HCs or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001). In some other applications (e.g., PU block), there can be problems with uncontrollable exotherms when using purely CO₂ (water) systems. CO₂/water blowing agent is used in extruded polystyrene boardstock in markets where thermal efficiency is not critical; however, in some applications, higher densities or lower conversion may offset the low costs of CO₂/water. In some cases, costs associated with overcoming technical challenges are so high that CO₂/water systems may be out of reach for many small and medium enterprises (IPCC, 2004).

Although LCD and CO₂ generated *in situ* have similar performance issues, the process limitations associated with each differ. Compared to LCD, fewer mechanical modifications are required when using *in situ* CO₂, and the foam manufacturer or PU spray foam applicator can be more certain of the final CO₂ content and overall foam properties (Alliance, 2001).

End-of-Life PU Appliance Foam Practices

There are several methods for disposal of PU foam, including landfilling and incineration, with or without ODS recovery and recycling or destruction. Two of the methods are described below, followed in Section IV.4.3.2 by specific analyses of the costs associated with each method.

Landfilling

Traditionally, most decommissioned foam products have ended up in landfills. Although the regulations related to the location and management of landfills have improved considerably, there is still concern about the rate of release of blowing agent from foam in the first weeks after entering the landfill (UNEP, 2002b).

Incineration

Incineration of foams in municipal solid waste incinerators (MSWIs) or waste-to-energy plants is a practical and highly competitive technique for destruction of PU foam. An advantage of this technique is that the foam can be incinerated without separating the foam matrix from the blowing agent prior to incineration, which lowers the cost and the risk of fugitive emissions (UNEP, 2002b).

IV.4.3.2 Description and Costs of Abatement Options

The following section describes all options in greater detail and presents a cost analysis for those options for which adequate cost data are available. The abatement options to reduce HFC emissions from the foam sector are presented by foam type: PU continuous and discontinuous panel foam, one-component foam, XPS boardstock foams, PU spray foams, and PU appliance foams. The technology options explored in this chapter are assumed to penetrate only the markets of new (i.e., not existing) foams. The remainder of this section provides a description of the economic assumptions for these abatement options. Throughout this discussion, we refer to Tables 4-4 and 4-5, which provide information on the technical applicability and the incremental maximum market penetrations assumed for each abatement option. These tables are discussed in greater detail in Section IV.4.3.3. A detailed description of the cost and emissions reduction analysis for each option can be found in Appendix H for this chapter.

PU Continuous and Discontinuous Panel Foam

The only abatement option that was considered for this category is replacing HFCs with HCs. This cost analysis estimates the breakeven carbon price for a hypothetical contractor to replace HFCs with HCs. In the base case scenario, the blowing agent constitutes 8.7 percent of the foam, by weight. In the base case, 1,048,600 pounds of blowing agent are consumed (UNEP, 2002a); hence, 12,052,874 pounds of foam are produced ($1,048,600/8.7\% = 12,052,874$). The foams manufactured with the alternative are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Although this end-use uses HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea, the analysis performed was based on a PU continuous and discontinuous panel foam contractor that uses HFC-134a. A contractor that uses HFC-245fa and HFC-365mfc/HFC-227ea would see higher cost savings for this replacement option because these HFCs are more expensive than HFC-134a. But, because HFC-245fa and HFC-365mfc/HFC-227ea have lower GWPs, the option would yield a lower ton of carbon equivalent (tCO₂eq) savings. This analysis is based on a hypothetical PU continuous and discontinuous panel foam contractor that uses approximately 1 million pounds of HFC-134a per year (ICF Consulting, 2004).

Cost factors that are addressed include the following:

- capital equipment costs such as costs of installing safety equipment including nonsparking equipment,
- increased cost of foam components (e.g., polyols, additives),
- increased consumption of foam components to compensate for increased foam density,
- worker safety,
- increased use of fire retardant, and
- incremental differences in the costs of blowing agents and the quantity required.

This option is technically applicable⁴ to all emissions from the newly produced continuous and discontinuous panel foams. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration of this option in the newly produced continuous and discontinuous panel market that uses HFC-134a will be 70 percent for the United States and 90 percent for the rest of the world by 2010, both rising to 100 percent by 2020 (see Table 4-5). Because the HFC is replaced by a HC, the reduction efficiency is assumed to be 100 percent. Assumptions specific to this substitution are presented in Appendix H for this chapter.

One-Component Foam

Two blowing agent replacement abatement options were considered for this end-use:

- replacing HFC-134a with propane/butane and
- replacing HFC-152a with propane/butane.

An analysis was performed based on a hypothetical one-component foam contractor that uses 288,000 pounds per year of HFC-134a or HFC-152a (ICF Consulting, 2004). In the base case, the blowing agent constitutes 8.7 percent of the foam, by weight; hence, 3,310,345 pounds of foam is produced ($288,000/8.7\%$

⁴ In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied. Because this option examines the replacement of HFC-134a with HCs in specific end-uses and cannot be retroactively applied to HFC-134a foam that has already entered the market, the technical applicability is the percentage of baseline foam emissions that are HFC-134a from continuous and discontinuous panels placed on the market after 2004. Other factors will affect the market penetration of the option assumed in this analysis.

= 3,310,345). This cost analysis estimates the breakeven carbon price for this hypothetical contractor to replace HFC-134a or HFC-152a with HCs (for details, see Appendix H).

Costs addressed include the following:

- capital equipment costs,
- increased cost of foam components (e.g., polyols, additives),
- increased consumption of foam components to compensate for increased foam density,
- worker safety,
- increased use of fire retardant, and
- incremental differences in the costs of blowing agents and the quantity required.

Replacing HFC-134a with HCs for One-Component Foam

This option is technically applicable to all HFC-134a emissions from the newly produced one-component foams. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration for this option in the newly produced one-component market that uses HFC-134a would be 70 percent for the United States and 90 percent for the rest of the world in 2010, both increasing to 100 percent by 2020 (see Table 4-5); reduction efficiency is assumed to be 100 percent. Assumptions specific to this substitution are presented in Table H-4 in Appendix H.

One-Component: Replacing HFC-152a with HCs

This option is technically applicable to all HFC-152a emissions from the newly produced one-component foams. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration for this option in the newly produced one-component foam market that uses HFC-152a would be 70 percent for the United States and 90 percent for the rest of the world by 2010, both increasing to 100 percent by 2020 (see Table 4-5); reduction efficiency is assumed to be 100 percent.

XPS Boardstock Foams

One blowing agent replacement option was considered for this end-use:

Replacing HFC-134a and CO₂-based Blends with CO₂ (LCD)/Alcohol for XPS Boardstock Foams

An analysis was performed based on a hypothetical producer that manufactures approximately 1 billion board feet (bd-ft) of foam per year, across 10 lines, using HFC-134a and CO₂-based blends as the blowing agent. Various base case inputs and assumptions are presented in Table H-6 in Appendix H. This cost analysis estimates the breakeven carbon price for this hypothetical producer to replace an HFC-134a and CO₂-based blend with CO₂/alcohol in one of the 10 lines. Using this alternative, the foam manufactured is assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness of the foam in the application, where possible. Thus, incremental differences in indirect emissions and costs associated with energy penalties are negligible.

Cost factors that are considered include the following:

- blowing agent costs,
- capital equipment costs,
- increased consumption of foam components to compensate for increased foam density,
- incremental differences in the costs of blowing agents and the quantity required, and
- costs of lost capacity.

The baseline blowing agent for XPS boardstock is assumed to be an HFC-134a and CO₂-based blend. Although many XPS boardstock facilities currently use HCFCs, it is assumed that this use will be phased out under the Montreal Protocol and, hence, baseline alternative emissions are calculated assuming the phase-in of HFC-134a. This option is technically applicable⁵ to all emissions from newly produced XPS boardstock foam; that is, one could theoretically use CO₂ (LCD)/alcohol in any new XPS boardstock foam produced. The technical applicability of this option (i.e., the percent of foam sector emissions calculated as arising from new XPS boardstock foam) from 2005 to 2020, is presented in Table 4-4. The incremental maximum market penetration of this option into the newly produced XPS foam market is assumed to be 0 percent for the United States through 2020; 70 percent in 2010, rising to 90 percent by 2020 in all other developed countries and CEITs; and 70 percent in 2010, rising to 90 percent by 2020 for China (see Table 4-5). The option completely eliminates emissions of HFC-134a, where applied, and, hence, has a reduction efficiency of 100 percent. Assumptions specific to this substitution are explained below and are presented in Appendix H for this chapter.

PU Spray Foams

Two blowing agent replacement options were considered for this end-use:

- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water) and
- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with cyclopentane/ isopentane.

An analysis was performed based on a hypothetical PU spray foam contractor that produces approximately 127,000 pounds of foam per year using a 75/25 blend of HFC-245fa⁶ and CO₂ (water) as a blowing agent. The base case blowing agent constitutes approximately 10 percent of the foam, by weight. Various base case inputs and assumptions are presented in Table H-8 in Appendix H. The foams manufactured with the two alternatives are assumed to require an increase in thickness and density to compensate for lower insulating performance relative to HFC-blown foams. Thus, there are no incremental differences in indirect emissions and costs associated with energy penalties. Although both HFC-245fa and HFC-365mfc/HFC-227ea are used in this end-use, this analysis was based on a PU spray foam contractor that uses HFC-245fa. Cost factors that are addressed include the following:

- fire testing costs incurred by system houses for various formulations,
- sparking of roof top equipment units,
- capital equipment costs,
- employee training costs (HCs only),
- increased cost of foam components (e.g., polyols, additives),
- increased consumption of foam components to compensate for increased foam density,
- increased use of fire retardant, and
- incremental differences in the costs of blowing agents and the quantity required.

⁵ In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied. Because this option examines the replacement of HFC-134a with CO₂ in only XPS foam and cannot be retroactively applied to foam that has already entered the market, the technical applicability is the percentage of baseline foam emissions that arises from HFC emissions from XPS foam placed on the market after 2004. Hence, technical applicability, in this sense, refers to the percentage of foam sector emissions calculated as arising from post-2004 XPS foam. Other factors will affect the market penetration of the option assumed in this analysis.

⁶ The EU-15 countries use a blend of HFC-365mfc and HFC-227ea in ratios of 93:7 or 87:13, while Japan uses a blend of HFC-245fa and HFC-365mfc in ratios of 80:20 or 70:30. This report presents a cost analysis based on the 75/25 HFC-245fa/CO₂ blend and applies it globally as a representative estimate.

Annual emissions reductions were determined based on the estimated amount of blowing agent consumed by the hypothetical contractor and from the emissions profile used in the Vintaging Model (see Table 4-1).

PU Spray: Replacing HFC-245fa/CO₂ (Water) and HFC-365mfc/HFC-227ea with CO₂ (Water)

This option is technically applicable⁷ to all emissions from the newly manufactured spray polyurethane foam market, but the assumed market penetration is tempered by the existence of another feasible option (i.e., HCs). The technical applicability of this option as well as other options from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration for this option into the newly formulated polyurethane spray foam market is 5 percent for the United States in 2010, and 8 percent for the rest of the world, both rising to 20 percent by 2020 (see Table 4-5); the reduction efficiency is assumed to be 100 percent because the HFC blowing agent is completely replaced (the GWP of CO₂ is not included in the analysis). For cost estimating purposes, this option assumes that the baseline blowing agent is a 75/25 blend of HFC-245fa and CO₂.

PU Spray: Replacing HFC-245fa/CO₂ (Water) and HFC-365mfc/HFC-227ea with HCs

The difference in costs between this abatement option and replacing HFC-245fa/CO₂ with CO₂ is the cost of training workers in handling, storing, and using HCs. For cost-estimating purposes, the baseline blowing agent is assumed to be a 75/25 blend of HFC-245fa and CO₂, while the alternative blowing agent is assumed to be an 80/20 blend of cyclopentane and isopentane. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration of this option in the newly produced PU spray foam market would be 10 percent for the United States and 5 percent for the rest of the world in 2010, rising in later years to 30 percent in the United States and 15 percent in the rest of the world (see Table 4-5); reduction efficiency is assumed to be 100 percent. There could be some safety and liability concerns associated with this substitution, which could lead to reduced market penetration or increased cost of this option.

PU Appliance Foams: Replacement Options

Two blowing agent replacement abatement options were considered for this end-use:

- replacing HFC-134a with cyclopentane/isopentane and
- replacing HFC-245fa and HFC-365mfc/HFC-227ea and with cyclopentane/isopentane.

This scenario examines a hypothetical facility that manufactures approximately 536,000 refrigerators and consumes about 1.68 million pounds (0.00076 Mt) of blowing agent annually. The blowing agent was assumed to constitute approximately 12 percent of the foam. The costs of producing a refrigerator using each blowing agent (e.g., HFC-134a, HFC-245fa, and cyclopentane/isopentane) were provided by the refrigeration industry. Data have been aggregated to protect confidential business information. This scenario was developed for a facility manufacturing large appliances typically used in the United States. While other markets may use different-sized refrigerators, and hence per-appliance factors may differ, this analysis assumes that the resulting cost per HFC emissions abated (dollars per tCO₂e_q) is approximately the same. Factors considered in these data include the following:

⁷ In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied. Because this option examines the replacement of HFCs with CO₂ in a specific end-use and cannot be retroactively applied to foam that has already entered the market, the technical applicability is the percentage of baseline foam emissions from PU spray foam placed on the market after 2004. Other factors will affect the market penetration of the option assumed in this analysis.

- capital costs to convert;
- blowing agent costs;
- foam costs, including density considerations;
- high-impact polystyrene (HIPS) and acrylonitrile-butadiene-styrene (ABS) liner costs;
- additional costs required to meet the U.S. 2001 National Appliance Energy Conservation Act (NAECA) energy efficiency standards; and
- the energy gap between different blowing agents and energy consumption increase as a result of the conversion.

HFC emissions reductions over time were derived from the emissions profile used in the Vintaging Model (see Table 4-1). These emissions account for gases released from the manufacturing process, annual release, disposal, and post disposal. Because the cost data are based on the assumption that the refrigerators manufactured using various blowing agents meet the same energy-efficiency standards, there are no incremental differences in indirect emissions and costs resulting from energy-efficiency differences.

PU Appliance: Replacing HFC-134a with HCs

This option is technically applicable⁸ to all HFC-134a emissions from newly manufactured PU appliance foam. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration in 2010 for this option in the newly manufactured appliance market that uses HFC-134a would be 25 percent for the United States and 85 percent for the rest of Annex I, rising to 70 percent and 90 percent, respectively, by 2020 (see Table 4-5). Because the HFC is completely replaced, the reduction efficiency is 100 percent.

PU Appliance: Replacing HFC-245fa and HFC-365mfc/HFC-227ea with HCs

Although some manufacturers may use HFC-365mfc/HFC-227ea instead of HFC-245fa, this analysis was performed based on the cost to replace HFC-245fa in PU appliance foams. This option is technically applicable to all emissions from the newly produced PU appliance foams that use HFC-245fa and HFC-365mfc/HFC-227ea. The technical applicability of this option from 2005 to 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration of this option into the newly manufactured appliance market that uses HFC-245fa and HFC-365mfc/HFC-227ea is 15 percent for the United States in 2010 rising to 50 percent by 2020. For all other countries, the market penetration in 2010 is 85 percent, rising to 90 percent by 2020 (see Table 4-5). Because the HFC is completely replaced, the reduction efficiency is 100 percent.

PU Appliance: End-of-Life Options

In addition to the two blowing agent replacement options considered above, two end-of-life abatement options were considered for this end-use:

- automated process with foam grinding, HFC adsorption, and foam landfilling in PU appliance foam and
- manual process with foam incineration in PU appliance foam.

⁸ In this report, the term “technically applicable” refers to the emissions to which an option can theoretically be applied. Because this option examines the replacement of HFC-134a with HCs in a specific end-use and cannot be retroactively applied to foam that has already entered the market, the technical applicability is the percentage of baseline foam emissions from appliance foam made with HFC-134a and placed on the market after 2004. Other factors will affect the market penetration of the option assumed in this analysis.

The baseline emissions are based on the assumption that the remainder of the blowing agent contained in the appliance foam is released after the foam's end of life, as shown in Table 4-1. Different technologies exist for abating end-of-life emissions in PU appliance foams. These technologies include landfilling the foam after recovering the blowing agent (which could either be destroyed or reclaimed and sold back to the market) and incinerating the foam (and the remaining blowing agent) in a Municipal Solid Waste Incinerator (MSWI) or waste-to-energy plant. This analysis analyzes the landfilling after recovering HFC and the MSWI options. This analysis assumes that when the HFC is recovered, it will still have value and hence contribute revenue to the process. HFC-134a and HFC-245fa are used in PU appliance foam in some locations. To account for the chemicals' different GWPs and costs, this analysis assumes that half of the appliances processed use HFC-134a and the other half use HFC-245fa. Further market research could refine this assumption.

Appendix H for this chapter presents cost estimates for each step involved in the removal or destruction of HFC contained in the foam, either through MSWI or grinding/adsorption/landfilling. Costs are presented in terms of dollars per refrigerator and in dollars per pound of HFC abated. This analysis uses the best cost information available; however, the costs presented should be considered illustrative rather than definitive. The analysis is done using the U.S. market as an example, recognizing that a U.S. refrigerator/freezer is typically larger than those used in other parts of the world. The final results (i.e., cost per unit of emissions abated) are applied to other regions because it is felt that the relative costs and emissions abated should scale roughly linearly to smaller appliances used elsewhere. All assumptions are based on a side-by-side refrigerator model.

The following two basic methods of handling appliances to abate blowing agent emissions are examined:

- **Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling.** This method involves purchasing a sophisticated system where the appliance is brought into the system without much preparation. The system shreds the appliance and uses various techniques such as magnets and eddy current to separate the metals, plastics, and foams. The blowing agent (and the refrigerant) is collected by adsorption⁹ onto a carbon substrate. Typically, the adsorbed gases are then incinerated, or they can be reclaimed and sold back into the market. These systems are capital-intensive, costing \$3,646,308 (JACO, 2004); however, once established, the manual labor is reduced. This type of process is generally only cost effective if a high flow of appliances (i.e., hundreds of thousands per year) is achieved.
- **Manual Process with Foam Incineration.** This method uses mostly manual labor to evacuate and recycle the refrigerant, drain and recycle the compressor oil, and disassemble the appliances, recovering and recycling glass shelves, plastic interior parts, steel, aluminum and other valuable metals. The foam is removed in large pieces, which can be quickly sealed in plastic bags to prevent further off-gassing of the blowing agent, and sent for incineration.

Cost factors that are addressed include the following:

- collection and consolidation of appliances,
- transportation of appliances to processing/disassembly location,
- disassembly and processing of appliances,

⁹ Other methods of blowing agent recovery are possible. For instance, some plants use liquid nitrogen to mitigate explosion potential with HC units. The nitrogen also serves to liquefy and collect the blowing agent.

- transportation of foam to landfilling or incineration location, and
- landfilling or incineration of foam.

Assumptions common to both the automated process with landfilling and the manual process with incineration abatement options are presented in Appendix H for this chapter.

PU Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling

The technical applicability of this option from 2005 through 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration of this option in the appliance foam market in 2020 would be 10 percent in the United States, 95 percent in Europe and Japan, and 70 percent in the rest of the developed world (see Table 4-5).

PU Appliance: Manual Process with Foam Incineration

The technical applicability of this option from 2005 through 2020 is presented in Table 4-4. This analysis assumes that the incremental maximum market penetration of this option in the appliance foam market in 2020 would be 30 percent in the United States and 10 percent in other developed countries except for the EU-15 and Japan, where the option is assumed not to penetrate the market.

IV.4.3.3 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 4-3 presents a summary of the assumed reduction efficiency, while Table 4-4 shows the technical applicability of the abatement options. Technical applicability values are based on the percentage of total foam emissions from each end-use and are derived from the baseline emissions methodology described in Section IV.4.2.1. The blowing agent replacement options explored in this chapter are assumed to penetrate only new (not existing) equipment, where “new” equipment is defined as equipment manufactured in 2005 or later.

Table 4-3: Reduction Efficiency of Foam Options (Percent)

Option	Reduction Efficiency
PU appliance: HFC-134a to HC	100.0
PU appliance: HFC-245fa and HFC 365mfc/HFC-227ea to HC	100.0
PU appliance: automated process with foam grinding and landfilling	90.0
PU appliance: manual process with incineration	90.6
PU spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to HC	100.0
PU spray: HFC-245fa/CO ₂ (water) and HFC-365mfc/HFC-227ea to CO ₂ (water)	100.0
XPS boardstock: HFC-134a/CO ₂ to CO ₂ /alcohol	100.0
One-component: HFC-134a to HC	100.0
One-component: HFC-152a to HC	100.0
PU continuous and discontinuous panel foam: HFC-134a to HC	100.0

A summary of the incremental maximum market penetrations assumed for the abatement options considered is presented in Tables 4-5 and 4-6.

To calculate the percent of emissions reductions off the total foams baseline for each abatement option, the percent of baseline emissions from Table 4-4 (i.e., technical applicability) is multiplied by the market penetration values from Table 4-6 and reduction efficiencies from Table 4-3. For example, to determine the percentage reduction off the 2020 baseline for replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)/alcohol in the XPS foam option in Japan, the following calculation is used:

$$\text{Technical applicability} \times \text{Incremental maximum market penetration} \times \text{Reduction efficiency} =$$

$$29\% \times 83\% \times 100\% \approx 24\%$$

Thus, using the assumptions in this analysis, applying this chemical replacement option could reduce Japan's baseline emissions by approximately 24 percent in 2020. This figure, along with the other emissions reduction potentials, is shown in Table 4-7.

Table 4-8 summarizes the cost assumptions used for the foam options presented in the discussions above.

IV.4.4 Results

IV.4.4.1 Data Tables and Graphs

Table 4-9 and 4-10 provide a summary of the potential emissions reductions at various breakeven costs by country/region in 2010 and 2020, respectively. The costs to reduce 1 tCO₂eq are presented for a discount rate of 10 percent and a tax rate of 40 percent.

Table 4-11 presents the costs, in 2000\$, to reduce 1 tCO₂eq for a discount rate scenario of 10 percent and a tax rate of 40 percent, for all the options analyzed. The results are ordered by increasing costs per tCO₂eq. Also presented are the emissions reduced by the option, in MtCO₂eq and percentage of the foam baseline, and cumulative totals of these two figures. Figures 4-2 and 4-3 present MACs for this sector at 10 percent discount rates and 40 percent tax rates in 2010 and 2020, respectively.

IV.4.4.2 Uncertainties and Limitations

This section focuses on the uncertainties associated with the cost estimates presented in this report.

Conversion Costs

In general, industry has indicated that there will be additional conversion or "learning curve" costs, which are short-term costs incurred as a result of yield, rate, and density penalties associated with conversion uncertainties as well as technical support costs. Such costs are highly variable and are not addressed in the analysis.

Capital and Annual Costs

A major uncertainty of this analysis is the cost of the abatement technologies. Currently, almost all of the costs for abatement options are available only for the United States. Thus, all U.S. capital and annual costs were applied internationally, other than the capital costs for the spray foam option, for which we had country-specific information for Japan and EU-15. However, costs may be higher internationally due to transportation and tariffs associated with purchasing the technology from abroad, or may be lower if there is domestic production of these technologies. In addition, for some abatement options, U.S. capital and annual costs were obtained in 2001; thus, these costs may be somewhat out of date.

Table 4-4: Technical Applicability of Foam Options (Percent)

Option	United States				Europe				Japan				All Other Developed Countries				CEITs				Non-Annex I Countries (China)			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
PU appliance: HFC-134a to HC	3	2	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU appliance: HFC-245fa and HFC-365mfc/HFC-227ea to HC	25	13	12	11	9	11	10	9	2	4	4	4	20	23	23	20	0	0	0	0	0	0	0	0
PU appliance: automated process with foam grinding, HFC adsorption, and foam landfilling	28	15	15	15	9	11	10	9	2	4	4	4	20	23	23	20	0	0	0	0	0	0	0	0
PU appliance: manual process with foam incineration	28	15	15	15	9	11	10	9	2	4	4	4	20	23	23	20	0	0	0	0	0	0	0	0
PU spray: HFC-245fa and HFC-365mfc/HFC-227ea to HC	52	34	38	40	18	25	29	28	19	28	33	36	17	31	36	36	0	0	0	0	0	0	0	0
PU spray: HFC-245fa, or HFC-365mfc/HFC-227ea to CO ₂	52	34	38	40	18	25	29	28	19	28	33	36	17	31	36	36	0	0	0	0	0	0	0	0
XPS boardstock: HFC-134a to CO ₂ /alcohol	0	41	38	33	26	22	19	15	37	33	31	29	0	0	0	0	0	4	8	8	0	0	0	0
One-component: HFC-134a to HC	0	1	1	1	11	3	3	2	1	1	1	1	0	0	0	0	100	96	92	92	100	100	100	100
One-component: HFC-152a to HC	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU continuous and discontinuous panel: HFC-134a to HC	1	1	1	1	8	9	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: Assumed technical applicability of options is presented as a percentage of total foam sector baseline emissions.

Table 4-5: Incremental Maximum Market Penetration Expressed as a Percentage of New Emissions for Which the Options Apply

Option	United States				Europe				Japan				All Other Developed Countries				CEITs				Non-Annex I Countries (China)			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
PU appliance: HFC-134a to HC	0	25	50	70	65	85	90	90	65	85	90	90	65	85	90	90	65	85	90	90	65	85	90	90
PU appliance: HFC-245fa and HFC-365mfc/HFC-227ea to HC	0	15	30	50	65	85	90	90	65	85	90	90	65	85	90	90	65	85	90	90	65	85	90	90
PU appliance: automated process with foam grinding, HFC adsorption, and foam landfilling	0	0	5	10	0	0	0	95	0	0	0	95	0	0	0	70	0	0	0	0	0	0	0	0
PU appliance: manual process with foam incineration	0	0	20	30	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
PU spray: HFC-245fa and HFC-365mfc/HFC-227ea to HC	5	10	20	30	0	5	10	15	0	5	10	15	0	5	10	15	0	5	10	15	0	5	10	15
PU spray: HFC-245fa, or HFC-365mfc/HFC-227ea to CO ₂	0	5	10	20	5	8	15	20	5	8	15	20	5	8	15	20	5	8	15	20	5	8	15	20
XPS boardstock: HFC-134a to CO ₂ /alcohol	0	0	0	0	50	70	70	90	50	70	70	90	50	70	70	90	50	70	70	90	50	70	70	90
One-component: HFC-134a to HC	50	70	90	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100
One-component: HFC-152a to HC	50	70	90	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100
PU continuous and discontinuous panel: HFC-134a to HC	50	70	90	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100	60	90	95	100

Table 4-6: Incremental Maximum Market Penetration Expressed as a Percentage of All Emissions

Option	United States				Europe				Japan				All Other Developed Countries				CEITs				Non-Annex I Countries (China)			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
PU appliance HFC-134a to HC	0	20	39	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU appliance HFC-245fa and HFC-365mfc/HFC-227ea, to HC	0	11	22	36	55	73	80	82	61	81	85	87	61	81	86	87	0	0	0	0	0	0	0	0
PU appliance automated process with foam grinding, HFC adsorption, and foam landfilling	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU appliance manual process with foam incineration	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU spray HFC-245fa and HFC-365mfc/HFC-227ea, to HC	4	8	15	23	0	4	7	11	0	3	6	10	0	4	8	11	0	0	0	0	0	0	0	0
PU spray HFC-245fa, or HFC-365mfc/HFC-227ea to CO ₂	0	4	7	14	4	6	11	15	3	5	10	14	5	7	12	16	0	0	0	0	0	0	0	0
XPS boardstock: HFC-134a/CO ₂ to CO ₂ /alcohol	0	0	0	0	45	61	63	78	49	67	68	83	0	0	0	0	0	70	70	86	0	0	0	0
One-component: HFC-134a to HC	0	70	90	100	60	90	95	100	60	90	95	100	0	0	0	0	60	90	95	100	60	90	95	100
One-component: HFC-152a to HC	0	70	90	100	60	90	95	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PU continuous and discontinuous panel: HFC-134a to HC	40	60	77	87	35	61	73	82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4-7: Emissions Reductions Off Total Foams Baseline (Percent)

	United States				Europe				Japan				All Other Developed Countries				CEITs				Non-Annex I Countries (China)			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
PU appliance HFC-134a to HC	0.0	0.5	0.9	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU appliance HFC-245fa and HFC-365mfc/ HFC-227ea to HC	0.0	1.4	2.7	3.9	5.2	7.8	8.3	7.3	1.1	3.1	3.4	3.5	12.0	19.0	19.8	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU appliance automated process with foam grinding, HFC adsorption, and foam landfilling	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU appliance manual process with foam incineration	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU spray HFC-245fa and HFC-365mfc/ HFC-227ea to HC	2.3	2.8	5.9	9.1	0.0	0.9	2.1	3.1	0.0	0.8	2.0	3.5	0.0	1.2	2.8	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU spray HFC-245fa and HFC-365mfc/ HFC-227ea to HC	0.0	1.3	2.8	5.6	0.7	1.6	3.2	4.3	0.5	1.5	3.2	5.0	0.8	2.1	4.4	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
XPS boardstock: HFC-134a/CO ₂ to CO ₂ /alcohol	0.0	0.0	0.0	0.0	11.7	13.4	11.8	11.7	18.1	21.8	21.0	24.1	0.0	0.0	0.0	0.0	0.0	2.7	5.4	6.9	0.0	0.0	0.0	0.0
One-component: HFC-134a to HC	0.0	0.6	0.6	0.6	6.4	3.1	2.9	2.4	0.8	0.9	0.9	0.9	0.0	0.0	0.0	0.0	60.0	86.5	87.6	92.0	60.0	90.0	95.0	100.0
One-component: HFC-152a to HC	0.0	0.0	0.0	0.0	0.5	0.7	0.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PU continuous and discontinuous panel: HFC-134a to HC	0.3	0.3	0.5	0.6	2.7	5.7	7.2	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	2.6	7.0	13.5	21.8	27.2	33.1	36.1	36.7	20.5	28.2	30.5	36.9	12.7	22.4	27.0	27.5	60.0	89.2	93.0	98.9	60.0	90.0	95.0	100.0

Table 4-8: Summary of Abatement Option Cost Assumptions

Option	Time Horizon (years):	Unit of Costs	Base One-Time Cost	Base Annual Cost	Base Annual Savings	Net Annual Cost
Continuous and discontinuous panel: HFC-134a to HC	25	Per contractor ^a	\$273,473	\$2,175,424	\$2,164,154	\$11,270
One-component: HFC-134a to HC	25	Per contractor ^b	\$341,841	\$292,711	\$639,673	–\$346,962
One-component: HFC-152a to HC	25	Per contractor ^b	\$341,841	\$292,711	\$342,779	–\$50,068
XPS: HFC-134a/CO ₂ to CO ₂ /Alcohol	25	Per manufacturer ^c	\$5,013,674	\$774,711	\$3,582,474	–\$2,807,764
PU spray: HFC-245fa/CO ₂ to CO ₂	25	Per contractor ^d	\$4,000	\$54,264	\$9,724	\$44,541
PU spray: HFC-245fa/CO ₂ to HC	25	Per contractor ^d	\$13,728 ^e	\$39,560	\$47,060	–\$7,500
PU appliance: HFC-134a to HC	25	Per factory ^f	\$50,000,000	\$0	\$1,506,160	–\$1,506,160
PU appliance: HFC-245fa to HC	25	Per factory ^f	\$50,000,000	\$11,202,400 ^h	\$0 ^h	\$11,202,400
PU appliance: automated process with foam grinding, HFC adsorption, and foam landfilling	25	Per facility ^g	\$3,646,308	\$1,848,159	\$481,809	\$1,366,350
PU appliance: manual process with foam incineration	25	Per facility ⁱ	\$182,315	\$456,528	\$48,239	\$408,289

^a Based on a hypothetical PU continuous and discontinuous panel foam contractor that produces approximately 12 million pounds of foam per year.

^b Based on a hypothetical one component foam contractor that produces approximately 3.3 million pounds of foam per year.

^c Based on a hypothetical XPS boardstock foam manufacturer that produces about 1 billion board-feet of foam per year.

^d Based on a hypothetical PU spray foam contractor that produces about 127,000 pounds of foam per year.

^e Only U.S.-based costs are presented in this summary table. However, EU-15 and Japan costs are \$21,251 and \$31,536 and are applied accordingly. U.S. costs are applied to all other countries.

^f Based on a hypothetical factory that manufactures 536,000 refrigerators per year.

^g Based on a facility that is assumed to process about 100,000 refrigerators per year.

^h Base annual savings are incorporated into the base annual costs.

ⁱ Based on a facility that is assumed to process 10,000 refrigerators per year.

Table 4-9: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Foams at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	2.06	2.41	2.41	2.66	2.66	3.40
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.02
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.02	0.02	0.02	0.02	0.02	0.02
Eastern Europe	0.00	0.01	0.01	0.01	0.01	0.01
EU-15	1.06	1.40	1.40	1.49	1.49	1.95
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.77	0.77	0.77	0.82	0.82	0.92
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.03	0.03	0.03	0.03	0.03	0.03
OECD	2.03	2.39	2.39	2.64	2.64	3.38
Russian Federation	0.02	0.02	0.02	0.02	0.02	0.02
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.19	0.21	0.21	0.31	0.31	0.39
World Total	2.08	2.43	2.43	2.69	2.69	3.43

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 4-10: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Foams at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	4.57	5.49	5.49	7.09	7.09	8.75
Australia/New Zealand	0.01	0.01	0.01	0.02	0.02	0.05
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.05	0.05	0.05	0.05	0.05	0.05
Eastern Europe	0.01	0.01	0.01	0.01	0.01	0.01
EU-15	2.00	2.86	2.86	3.34	3.34	4.17
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	1.37	1.37	1.37	1.61	1.61	1.77
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.05	0.05	0.05	0.05	0.05	0.05
OECD	4.52	5.44	5.44	7.04	7.04	8.71
Russian Federation	0.04	0.04	0.04	0.04	0.04	0.04
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	1.10	1.17	1.17	1.98	1.98	2.47
World Total	4.62	5.54	5.54	7.14	7.14	8.81

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 4-11: World Breakeven Costs and Emissions Reductions in 2020 for Foams

Reduction Option	Cost (2000\$/tCO ₂ eq)		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	DR=10%, TR=40%					
	Low	High				
XPS boardstock: HFC-134a/CO ₂ (LCD)—based blends to CO ₂ (LCD)/alcohol	−\$7.81	−\$7.81	2.49	8.7%	2.49	8.7%
PU Spray: HFC-245fa/CO ₂ (water) to HC	−\$5.19	−\$2.91	1.59	5.5%	4.08	14.2%
PU one-component HFC-134a to HC	−\$1.76	−\$1.76	0.48	1.7%	4.56	15.9%
PU one-component HFC-152a to HC	−\$0.15	−\$0.15	0.06	0.2%	4.62	16.1%
PU continuous and discontinuous: HFC-134a to HC	\$0.86	\$0.86	0.92	3.2%	5.54	19.3%
PU Appliance: automated process with foam grinding, HFC adsorption, and foam landfilling	\$36.07	\$36.07	0.01	0.0%	5.55	19.4%
PU Spray: HFC-245fa/CO ₂ (water) to CO ₂ (water)	\$41.84	\$41.84	1.42	5.0%	6.98	24.4%
PU appliance: HFC-134a to HC	\$42.06	\$42.06	0.17	0.6%	7.14	24.9%
PU appliance: manual process with foam incineration	\$82.54	\$82.54	0.04	0.1%	7.18	25.1%
PU appliance: HFC-245fa to HC	\$192.54	\$192.54	1.62	5.7%	8.81	30.7%

Market Penetrations

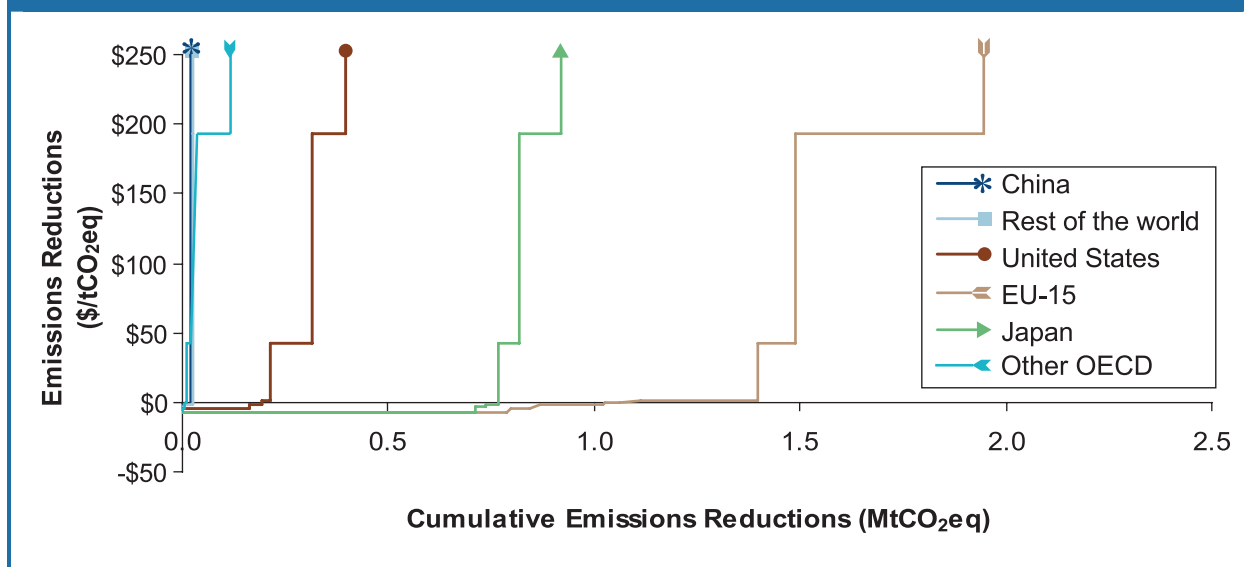
Market penetrations of abatement technologies are based on published reports and discussions with industry experts in the U.S. and EU-15. However, actual market penetrations of these technologies may be different. For example, market penetration rates and hence emissions reduction potentials may be higher in countries that are establishing climate policies.

PU Continuous and Discontinuous Panel Foam

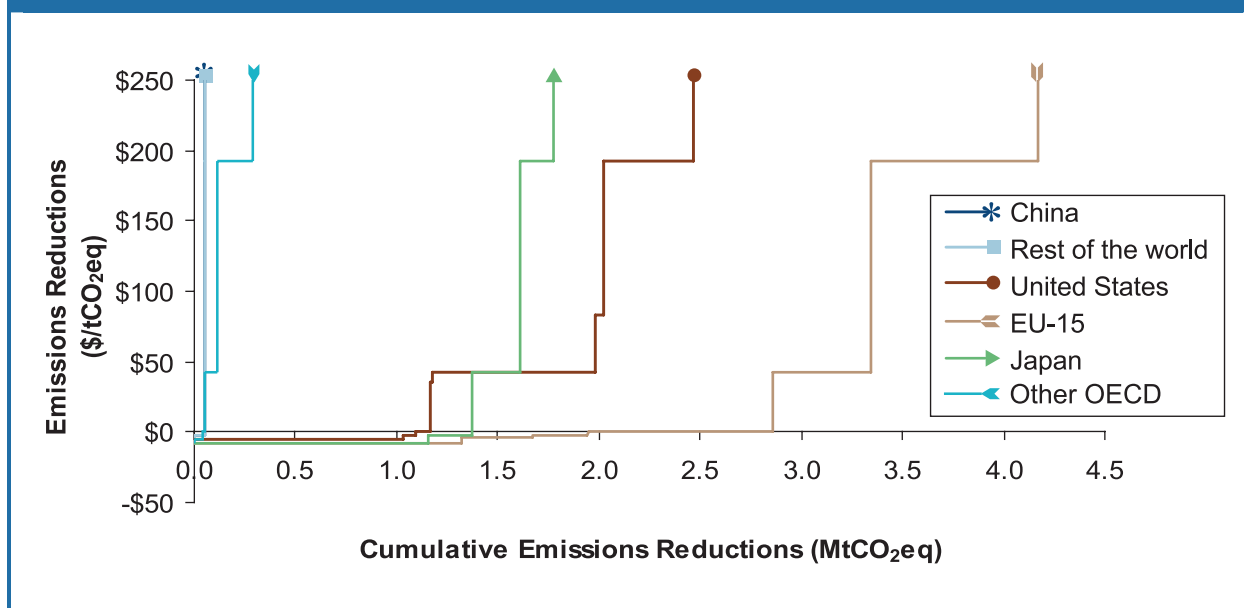
For PU continuous and discontinuous panel foam, the cost analysis was performed based on a contractor that uses HFC-134a; however, this end-use also uses HFC-245fa, and HFC-365mfc/HFC-227ea.

XPS Boardstock Foam

Capital and annual costs for abatement technologies of XPS boardstock foam were based on a consensus reached among industry representatives or averages of different estimates provided by different manufacturers. These averages may not reflect the full range of costs that might be experienced.

Figure 4-2: 2010 MAC for Foams, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 4-3: 2020 MAC for Foams, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.4.5 Summary

Baseline emissions of HFCs from foams are estimated to grow from 1.5 to 28.6 MtCO₂eq between 2000 and 2020. In 2020, OECD countries are assumed to account for almost 100 percent of the emissions, while U.S. emissions and EU-15 emissions are each assumed to account for about 40 percent of this total. The largest emissions growth is expected in the United States, from 0.3 MtCO₂eq in 2000 to 11.3 MtCO₂eq in 2020.

This analysis considers the following eight replacement emissions mitigation options for PU spray, PU appliance, XPS boardstock, PU continuous and discontinuous panel foam, and one-component foams, as well as the following two end-of-life options for PU appliance foams:

- replacing HFC-134a, HFC-245fa, and HFC-365mfc/HFC-227ea with HCs in PU continuous and discontinuous panel foam;
- replacing HFC-134a with HCs in one-component foam;
- replacing HFC-152a with HCs in one-component foam;
- replacing HFC-134a/CO₂ (LCD) with CO₂ (LCD)/alcohol in XPS boardstock foam;
- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with CO₂ (water) in PU spray foam;
- replacing HFC-245fa/CO₂ (water) and HFC-365mfc/HFC-227ea with HCs in PU spray foam;
- replacing HFC-134a with HCs in PU appliance foam;
- replacing HFC-245fa and HFC 365mfc/HFC-227ea with HCs in PU appliance foam;
- end-of-life PU appliance foam practice: automated process with foam grinding, HFC adsorption, and foam landfilling in PU appliance foam; and
- end-of-life PU appliance foam practice: manual process with foam incineration in PU appliance foam.

The emissions reduction benefits of each option were compared in each region. For spray end-uses, the costs associated with converting to alternative blowing agents differ between the United States, EU, and Japan. The costs per tCO₂eq of all other abatement options for these three regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be required to determine actual variability in costs across regions. This analysis shows that there are several cost-effective options available at the 10 percent discount rate and 40 percent tax rate that may be used to eliminate the use of HFCs and reduce HFC-associated emissions from foams.

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IV.5 HFC Emissions from Aerosols

IV.5.1 Introduction

Aerosol propellants are used in metered dose inhalers (MDIs), as well as a variety of consumer products. Historically, the majority of aerosol applications have used CFCs as propellants; however, efforts have been made to transition away from CFC propellants. As a result of initiatives under the Montreal Protocol, many pharmaceutical companies that produce MDIs have committed to develop alternatives to CFC-based MDIs. Furthermore, many consumer products, such as spray deodorants and hair sprays, and specialty aerosol uses, such as freeze spray and dust removal products, have successfully been reformulated with HC propellants or replaced with NIK substitutes such as pump sprays or solid and roll-on deodorants. Such transitions occurred in the United States as far back as 1977, when the country placed a ban on CFC propellants in non-MDI aerosols for nonessential uses.

Various HFCs have also been introduced as alternative propellants in aerosol applications. These HFCs include HFC-134a, HFC-152a, and HFC-227ea and are associated, respectively, with 100-year GWPs of 1,300, 140, and 2,900. Aerosol HFCs are emitted from pharmaceutical products (primarily MDIs)¹ and consumer and industrial products (primarily specialty aerosols).

The pharmaceutical aerosol industry is actively working to develop HFC-propellant MDIs, a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease (COPD). The earliest non-CFC substitute products used HFC-134a, but eventually the industry expects products to use HFC-227ea as well. In addition to MDIs that use propellants, dry powder inhalers (DPIs) can be used as a substitute for some MDIs. Because MDIs are medical devices, substitute propellants must meet far stricter performance and toxicology specifications than required for most other products. In the United States, for example, the Food and Drug Administration (FDA) must approve MDIs reformulated with an alternative propellant before they can enter the market.

Chemical manufacturers are also marketing HFCs, especially HFC-152a and HFC-134a, as aerosol propellants in consumer products, primarily for use in specialty applications. This is particularly true for applications where flammability or volatile organic compound (VOC) emissions and their impact on urban air quality are of concern. If HFC use is accelerated, public concern over these emissions may increase. This concern will likely spur the aerosol industry to promote responsible use of these chemicals, for instance, by implementing emissions abatement options examined in this report (UNEP, 1999).

IV.5.2 Baseline Emissions Estimates

IV.5.2.1 Emissions Estimating Methodology

Description of Methodology

Specific information on the emissions model used to calculate ODS substitute emissions from all sectors calculates aerosol emissions is described below.

The USEPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes in the United States, including HFCs. Emissions

¹ This analysis excludes non-MDI aerosols produced by the pharmaceutical industry such as bandage sprays.

baselines from non-U.S. countries were derived using country-specific ODS consumption estimates as reported under the Montreal Protocol in conjunction with Vintaging Model output for each ODS-consuming end-use sector. For sectors where detailed information was available, these data were incorporated into country-specific versions of the Vintaging Model to customize emissions estimates. In the absence of country-level data, these preliminary estimates were calculated by assuming that the transition from ODSs to HFCs and other substitutes follows the same general substitution patterns internationally as observed in the United States. From this preliminary assumption, emissions estimates were then tailored to individual countries or regions by applying adjustment factors to U.S. substitution scenarios, based on relative differences in economic growth, rates of ODS phaseout, and the distribution of ODS use across end-uses in each region or country.

Emissions Equations

All HFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, all of the annual production of aerosol propellants is assumed to be released to the atmosphere. The following equation describes the emissions from the aerosols sector:

$$E_j = Qc_j, \quad (5.1)$$

where

- E_j = Total emissions of a specific chemical in a year j from use in aerosol products, by weight.
- Qc_j = Total quantity of a specific chemical contained in aerosol products sold in the year j , by weight
- j = Year of emissions

For aerosols, two separate baseline emissions were created; one baseline tracks HFC emissions from the MDI industry, while the other estimates HFC emissions from consumer and specialty products (i.e., non-MDI aerosols).

Regional Adjustments

The adjustment factor assumptions used in the global aerosol emissions estimating methodology include both economic and timing adjustment factors. The timing factors reflect that some nations are not moving at the same pace away from using CFCs and toward using HFCs as other nations are. For all ODS end-uses, by 2005, non-Annex I (i.e., developing) countries are assumed to be 75 percent through the CFC transition, and by 2010, the CFC transition should be complete. These timing factors are partially offset by generally higher growth rates in developing countries.

In addition, the methodology used to estimate global aerosol emissions includes an adjustment specific to non-MDI aerosols. This adjustment was necessary because the ban on CFC use in aerosols caused the United States to transition out of CFCs earlier than other countries. Therefore, the unweighted U.S. consumption of non-MDI aerosol ODS substitutes (including a large market segment that transitioned into NIK or HC substitutes) was used as a proxy for U.S. 1990 non-MDI ODS consumption. For countries other than the United States, it was then assumed that 15 percent of the non-MDI aerosols ODS consumption transitioned to HFCs, while the remainder is assumed to transition to NIK or HC alternatives.

IV.5.2.2 Baseline Emissions

Table 5-1 and Figure 5-1 display total HFC emissions estimates in million metric tons of carbon dioxide equivalent (MtCO₂eq) for the MDI aerosol sector, while Table 5-2 and Figure 5-2 represent the non-MDI aerosols sector. Both HFC-134a and HFC-227ea are expected to be emitted from using MDIs in the future as substitutes for CFCs. The MDI emissions baseline accounts for all emissions of HFC-227ea from the aerosols sector. Non-MDI emissions are responsible for the majority of the HFC-134a emissions from the aerosols sector (mainly for specialty applications) and all of the HFC-152a emissions (mostly formulated consumer products).

IV.5.3 Cost of HFC Emissions Reductions for Aerosols

This section presents a cost analysis for achieving HFC emissions reductions from the emissions baselines presented in Tables 5-1 and 5-2. The cost analysis for the MDI option assumes a 15-year project lifetime; all cost analyses for the non-MDI emissions reduction options assume a 10-year project lifetime. Each abatement option is described below.

IV.5.3.1 Description and Cost Analysis of Abatement Options

Four potential mitigation options are analyzed in this report. The first mitigation option has the potential to abate emissions from the MDI baseline (Table 5-1), while the other three options have the potential to abate emissions from the non-MDI baseline (Table 5-2). The options are as follows:

- MDI replacement with DPIs (DPI [MDI])
- non-MDI replacement with lower GWP HFCs (HFC-134a to HFC-152a [non-MDI])
- non-MDI replacement with NIK alternatives (HFC to NIK [non-MDI])
- non-MDI replacement with HC aerosol propellants (HFC to HC [non-MDI])

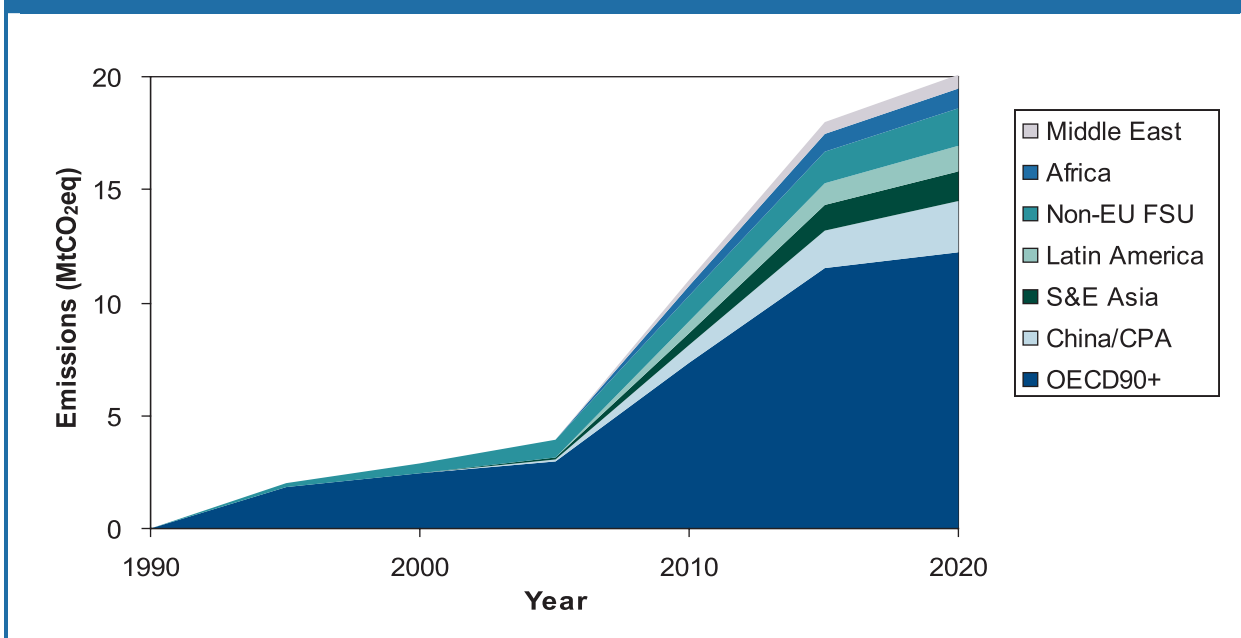
DPIs have been authorized as a substitute for some HFC-propellant MDIs. The non-MDI baseline includes emissions from specialty aerosol uses such as tire inflators, electronics cleaning products, dust removal, freeze spray, signaling devices, and mold release agents, as well as consumer products such as hairsprays, mousse, deodorants and antiperspirants, household products, and spray paints (Arthur D. Little, 1999). HFCs are currently used when flammability issues cannot easily be overcome, such as tire inflators and air signaling horns that use HFC-134a to avoid potential explosivity associated with highly flammable propellants like propane or butane (Arthur D. Little, 1999). HFC-152a has been used in dusters since 1993 (UNEP, 1999), and as a replacement for HFC-134a in general aerosol applications. Converting to HFC-152a in these applications is a reduction strategy that has had significant success thus far and is expected to continue. The other options to reduce HFC emissions from non-MDI aerosol applications addressed in this analysis include NIK replacement and HC aerosol propellants. Other options, such as using carbon dioxide as a propellant, may also exist but have not been addressed in this analysis because specific information is lacking.

The remainder of this section describes the economic assumptions for these four abatement options. A detailed description of the cost and emissions reduction analysis for each option can be found in Appendix I for this chapter.

Table 5-1: Total Baseline HFC Emissions Estimates from MDI Aerosols (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	0.0	0.4	0.9
Annex I	2.8	8.5	13.8
Australia/New Zealand	0.2	0.3	0.4
Brazil	0.0	0.1	0.2
China	0.0	0.7	2.2
Eastern Europe	0.1	0.3	0.4
EU-15	1.9	2.8	3.8
India	0.0	0.2	0.6
Japan	0.1	0.9	1.6
Mexico	0.0	0.3	0.7
Non-OECD Annex I	0.4	1.3	1.8
OECD	2.4	7.6	12.8
Russian Federation	0.4	1.1	1.5
South & SE Asia	0.0	0.3	0.8
United States	0.1	2.7	5.5
World Total	2.9	11.0	20.1

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

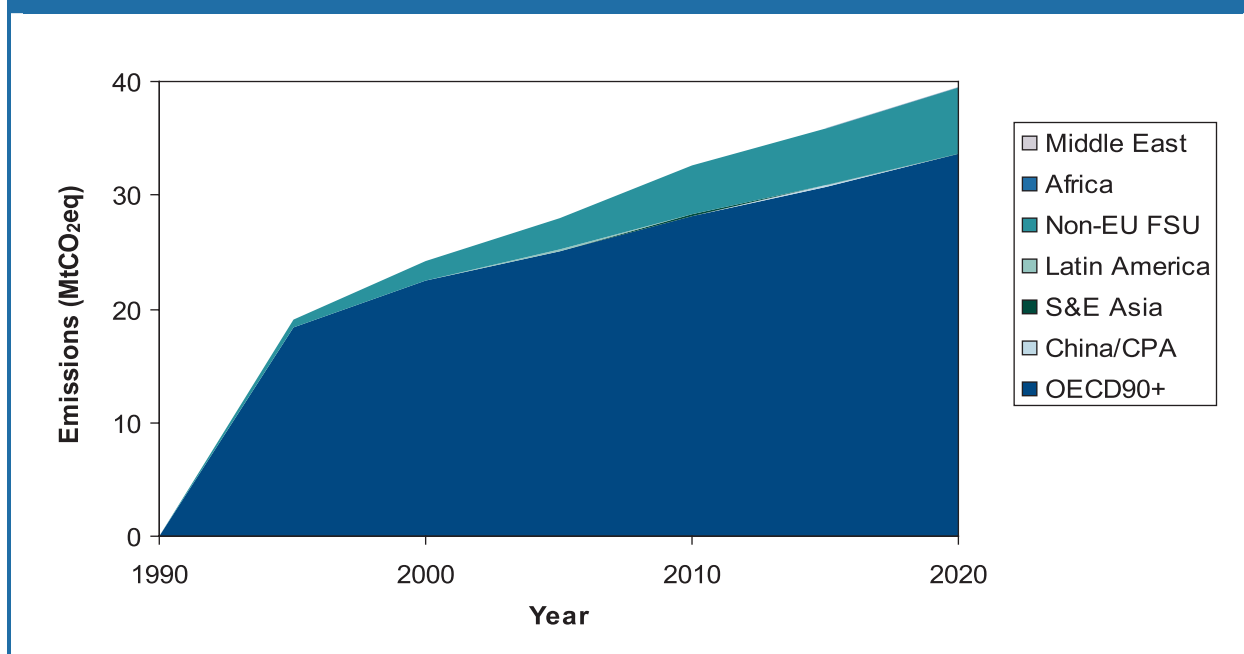
Figure 5-1: Total Baseline HFC Emissions Estimates from MDI Aerosols (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = Organisation for Economic Co-operation and Development.

Table 5-2: Total Baseline HFC Emissions Estimates from Non-MDI Aerosols (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	24.1	32.6	39.4
Australia/New Zealand	0.7	0.9	1.1
Brazil	0.0	0.0	0.0
China	0.0	0.0	0.0
Eastern Europe	1.1	2.9	4.0
EU-15	10.5	11.8	13.3
India	0.0	0.0	0.0
Japan	0.0	0.0	0.0
Mexico	0.0	0.0	0.0
Non-OECD Annex I	2.1	5.5	7.2
OECD	22.0	27.1	32.2
Russian Federation	1.6	4.2	5.5
South & SE Asia	0.0	0.0	0.0
United States	9.9	12.1	14.8
World Total	24.2	32.7	39.5

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 5-2: Total Baseline HFC Emissions Estimates from Non-MDI Aerosols (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = Organisation for Economic Co-operation and Development.

MDI: Replacement with Dry Powdered Inhalers (DPIs)

As MDIs transition away from CFC use, alternatives such as HFC propellants, DPIs, and oral medications are being developed. Although HCs have replaced CFCs as propellants in many commercial aerosols, they have been found to be unacceptable for use in MDIs (International Pharmaceutical Aerosol Consortium [IPAC], 1999). Given the unique medical requirements for developing MDIs, and the fact that the industry has been investing heavily in the development of HFC technologies, an aerosol replacement for HFC-based MDIs is unlikely to be developed within the time frame of this analysis. Globally, the number of HFC MDIs used has grown to more than 100 million in 2001 (UNEP, 2002). Rather than developing new alternatives that use HFCs, some MDI patients may turn to DPIs, oral medication, or other NIK alternatives. In 2001, the number of multidose DPIs used worldwide was estimated at 65 million (UNEP, 2002).² This analysis examines the option of further replacing HFC-based MDIs with DPIs because of its technical feasibility and demonstrated success in the MDI market.

DPIs are a viable option with most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder can be inhaled and deposited in the lungs from DPIs as with MDIs, but only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates (March Consulting Group, 1999; UNEP, 2002). Other issues that doctors and patients consider when choosing a treatment device include the patient's manual dexterity, ability to adapt to a new device, and perception of the effectiveness of the medicine, and the taste of any added ingredients (Price et al., 2004). It is important to note that the choice of treatment, including the type of propellant used in MDIs, is a medical decision involving the pharmaceutical industry, FDA or other regulatory authority, and ultimately doctors and their patients. Doctors and their patients will be involved in selecting the method of therapy, treatment regimen, and type of device(s) and active ingredients(s) that will prove most effective for particular individuals (IPAC, 1999).

In 1998, DPI use was estimated to represent 17 percent of all inhaled medication (i.e., inhaler units) worldwide and had increased to 27 percent by 2002 (UNEP, 2002). DPIs may represent a viable alternative, as suggested by their increased use in Europe; for example, in Holland they account for more than 65 percent of inhaled medication (UNEP, 2002). The use of newly available DPIs is on the rise in the United States, where DPIs made up 14 percent of the total U.S. market share as of mid-2002 (UNEP, 2002). There is also a trend toward developing a broad range of oral treatments that would be swallowed, rather than inhaled and may be introduced over the next 10 to 20 years. These new medications may affect MDI use, although they will not likely replace inhaled MDI therapy entirely.

This analysis assumes that DPIs are technically applicable³ to all HFC emissions from MDIs. However, because of the limitations in their use for severe asthma patients and young children, and the difficulties experienced in hot and humid climates, this analysis assumes a global incremental maximum market penetration into the HFC-based MDI market of 0 percent in 2005, increasing up to 50 percent in 2020 (Table 5-3). DPIs do not use HFCs; hence, they have a 100 percent reduction efficiency. To the extent

² Multiple-dose DPIs contain premeasured doses that provide treatment for a day or up to 1 month. Single-dose DPIs are also available for which only one dose can be loaded at a time (UNEP, 2002).

³ In this report, the term "technically applicable" refers to the emissions to which an option can theoretically be applied. Because DPIs can eliminate emissions from MDIs, they are technically applicable to all MDI emissions but are not technically applicable to non-MDI emissions. Other factors will affect their application and the market penetration assumed in this analysis.

that health and technical concerns are adequately met, a transition in inhalation therapy away from propellant MDIs and toward NIK alternatives may occur over the next 10 to 20 years. The rapidity at which these changes will occur depends on product development cycles (generally about 10 years), cost-effectiveness, and manufacturing capacity (UNEP, 1999).

Non-MDI: Replacement with Lower GWP HFCs

Replacing higher GWP HFCs, such as HFC-134a, with a lower GWP HFC, such as HFC-152a, has the potential to greatly reduce emissions from the non-MDI aerosols sector. HFC-134a is the primary nonflammable propellant in certain industrial products. HFC-152a possesses only moderate flammability hazards and might therefore be acceptable for some applications (UNEP, 2002) but may present problems for other applications. This analysis assumes that converting to HFC-152a is technically applicable to all emissions of HFC-134a from the non-MDI baseline but is only adopted by some users. Non-MDI emissions of HFC-134a are calculated by the Vintaging Model to be 83 percent of total GWP-weighted non-MDI aerosol emissions. As shown in Table 5-3, the incremental maximum market penetration of this alternative is assumed to increase from 10 percent in 2005 to 50 percent in 2020. Because HFC-152a has a GWP of 140 (versus a GWP of 1,300 for HFC-134a), this substitution has an emissions reduction efficiency of 89.2 percent (i.e., the difference of the GWPs divided by the GWP of HFC-134a).

Non-MDI: Replacement with NIK Alternatives

NIK aerosol replacements include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These systems often prove to be better and more cost-effective options than HFC-propelled aerosols, particularly in areas where a unique HFC property is not specifically needed for a certain end-use. NIKs already occupy a sizable share of markets where they were introduced during the initial CFC phaseout. Since NIK products have already assumed much of the available non-MDI HFC aerosol market share, an incremental maximum market penetration of 5 percent was assumed in 2005 and 10 percent for years 2010, 2015, and 2020 (see Table 5-3). The analysis assumes that this option is technically applicable to all non-MDI emissions and has a reduction efficiency of 100 percent. The GWP of 538 was used to represent both HFCs being abated and was calculated using the weighted average of the U.S. HFC-134a and HFC-152a baseline emissions.

Non-MDI: Replacement with Hydrocarbon Aerosol Propellants

HC aerosol propellants are usually mixtures of propane, butane, and isobutane. Their primary advantage lies in their affordability; the price of HC propellants is less than one-tenth that of HFCs. The main disadvantages of HC aerosol propellants are flammability and VOC emissions concerns. HCs contribute to ground-level ozone and smog and therefore may be regulated in some areas. In applications and markets where flammability and/or VOC emissions are less of a concern, HCs already hold a sizable share. Since HC aerosol propellants have already penetrated a significant amount of the market, further penetration is limited because of flammability and VOC concerns. Hence, this analysis assumes an incremental maximum market penetration of 5 percent in 2005, expanding to 10 percent in later years. The analysis also assumes that converting to HCs is technically applicable to all non-MDI emissions, but that various factors including the flammability of HCs will limit the market penetration of this option. The reduction efficiency of this abatement option is taken to be 100 percent, since the HFC is completely replaced by an HC propellant with a very low GWP. The GWP of 538 was used to represent both HFCs being abated and was calculated using the U.S. weighted average of the HFC-134a and HFC-152a baseline emissions.

IV.5.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 5-3 summarizes the technical applicability and incremental maximum market penetration of the aerosol options presented in the discussions above.

Table 5-3: Technical Applicability and Incremental Maximum Market Penetration of Aerosol Options (Percent)^a

Option	Technical Applicability (All Years)	Incremental Maximum Market Penetration			
		2005	2010	2015	2020
DPI (MDI) ^b	100%	0%	5%	20%	50%
HFC to HC (non-MDI)	100%	5%	10%	10%	10%
HFC to NIK (non-MDI)	100%	5%	10%	10%	10%
HFC-134a to HFC-152a (non-MDI)	83% ^c	10%	25%	35%	50%

^a Assumed maximum market penetration of options is presented as a percentage of total sector emissions for which the options are applicable. The baseline market penetration is assumed to be zero to assess the emissions reductions possible due to increased use of each option.

^b Assumptions are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

^c Based on percentage of non-MDI aerosol emissions as determined by the Vintaging Model.

To calculate the percentage of emissions reductions off the applicable (i.e., MDI or non-MDI) aerosols baseline for each abatement option, the technical applicability, is multiplied by the market penetration value, and by the reduction efficiency of the option. For example, to determine the percentage reduction off the 2020 baseline for the conversion of HFC-134a aerosols to HFC-152a, the following calculation is performed:

Technical applicability x Market penetration in 2020 x Reduction efficiency

$$83\% \times 50\% \times 89.2\% \approx 37.0\%$$

Thus, using the assumptions in this analysis, converting from HFC-134a to HFC-152a could reduce over one-third of the non-MDI emissions baseline in 2020. This value, along with the other emissions reduction potentials, is shown in Table 5-4.

Table 5-4: Emissions Reductions Off the Total Applicable Aerosols Baseline (Percent)

Option	2005	2010	2015	2020
DPI (MDI) ^a	0.0	5.0	20.0	50.0
HFC to HC (non-MDI)	5.0	10.0	10.0	10.0
HFC to NIK (non-MDI)	5.0	10.0	10.0	10.0
HFC-134a to HFC-152a (non-MDI)	7.4	18.5	25.9	37.0

^a Calculated percentages are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

Table 5-5 summarizes the cost assumptions used for the aerosol options presented in the discussion above.

Table 5-5: Summary of Abatement Option Cost Assumptions

Option	Time Horizon (Years)	Unit of Costs	Base One-Time Cost (2000\$)	Base Annual Cost (2000\$)	Base Annual Savings (2000\$)	Net Annual Costs (2000\$/yr)
DPI (MDI)	15	Per metric ton of abated substance	\$0	\$571,400	\$0	\$571,400
HFC to HC (Non-MDI)	10	Per 10,000,000cans/yr requiring 2 oz. propellant each	\$325,000	\$0	\$2,001,456	–\$2,001,456
HFC to NIK (Non-MDI)	10	Per 10,000,000 cans/yr requiring 2 oz. propellant each	\$250,000	\$500,000	\$2,343,458	–\$1,843,458
HFC-134a to HFC-152a (Non-MDI)	10	Per 10,000,000 cans/yr requiring 2 oz. propellant each	\$500,000	\$0	\$1,090,257	–\$1,090,257

IV.5.4 Results

IV.5.4.1 Data Tables and Graphs

Tables 5-6 through 5-9 provide a summary of the potential emissions reduction opportunities at associated breakeven costs in 15-dollar increments at a 10 percent discount rate (DR) and 40 percent tax rate (TR). Tables 5-6 and 5-7 present the results for MDI Aerosols, for 2010 and 2020, respectively. As shown, in 2010 and 2020, emissions reduction opportunities are only available at a breakeven cost greater than 60 dollars per tCO₂eq for all regions. A world total emissions reduction of 0.55 MtCO₂eq is projected by 2010 and 10.06 MtCO₂eq by 2020, both at a breakeven cost greater than \$60/tCO₂eq.

Tables 5-8 and 5-9 present the results for the Non-MDI Aerosols sector for 2010 and 2020, respectively. In contrast to the MDI aerosol sector, the non-MDI sector emissions reduction opportunities are available at the lowest breakeven cost of \$0/tCO₂eq for several regions. A total emissions reduction of 12.6 MtCO₂eq is projected by 2010 and 22.54 MtCO₂eq by 2020, both at a breakeven cost below 1 dollar per tCO₂eq.

In Table 5-10, the costs, in 2000\$, to reduce tCO₂eq are presented for a discount rate scenario of 10 percent and a tax rate of 40 percent. Within the options that address non-MDI emissions, the results are ordered by increasing costs per tCO₂eq. Additionally, the emissions reduced by the option, in MtCO₂eq and percent of the aerosols (either MDI or non-MDI) baseline, as well as cumulative totals of these two figures are presented.

Table 5-6: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.02
Annex I	0.00	0.00	0.00	0.00	0.00	0.43
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.01
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.00	0.00	0.00	0.04
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.01
EU-15	0.00	0.00	0.00	0.00	0.00	0.14
India	0.00	0.00	0.00	0.00	0.00	0.01
Japan	0.00	0.00	0.00	0.00	0.00	0.05
Mexico	0.00	0.00	0.00	0.00	0.00	0.01
OECD Annex I	0.00	0.00	0.00	0.00	0.00	0.06
OECD	0.00	0.00	0.00	0.00	0.00	0.38
Russian Federation	0.00	0.00	0.00	0.00	0.00	0.06
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.02
United States	0.00	0.00	0.00	0.00	0.00	0.14
World Total	0.00	0.00	0.00	0.00	0.00	0.55

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 5-7: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.43
Annex I	0.00	0.00	0.00	0.00	0.00	6.91
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.18
Brazil	0.00	0.00	0.00	0.00	0.00	0.08
China	0.00	0.00	0.00	0.00	0.00	1.08
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.22
EU-15	0.00	0.00	0.00	0.00	0.00	1.88
India	0.00	0.00	0.00	0.00	0.00	0.29
Japan	0.00	0.00	0.00	0.00	0.00	0.82
Mexico	0.00	0.00	0.00	0.00	0.00	0.34
Non-OECD Annex I	0.00	0.00	0.00	0.00	0.00	0.89
OECD	0.00	0.00	0.00	0.00	0.00	6.40
Russian Federation	0.00	0.00	0.00	0.00	0.00	0.77
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.39
United States	0.00	0.00	0.00	0.00	0.00	2.74
World Total	0.00	0.00	0.00	0.00	0.00	10.06

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 5-8: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Non-MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.01	0.01	0.01	0.01	0.01	0.01
Annex I	12.56	12.56	12.56	12.56	12.56	12.56
Australia/New Zealand	0.34	0.34	0.34	0.34	0.34	0.34
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.01	0.01	0.01	0.01	0.01	0.01
Eastern Europe	1.13	1.13	1.13	1.13	1.13	1.13
EU-15	4.55	4.55	4.55	4.55	4.55	4.55
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	2.12	2.12	2.12	2.12	2.12	2.12
OECD	10.45	10.45	10.45	10.45	10.45	10.45
Russian Federation	1.61	1.61	1.61	1.61	1.61	1.61
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	4.67	4.67	4.67	4.67	4.67	4.67
World Total	12.60	12.60	12.60	12.60	12.60	12.60

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 5-9: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Non-MDI Aerosols at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.01	0.01	0.01	0.01	0.01	0.01
Annex I	22.46	22.46	22.46	22.46	22.46	22.46
Australia/New Zealand	0.61	0.61	0.61	0.61	0.61	0.61
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.03	0.03	0.03	0.03	0.03	0.03
Eastern Europe	2.25	2.25	2.25	2.25	2.25	2.25
EU-15	7.60	7.60	7.60	7.60	7.60	7.60
India	0.01	0.01	0.01	0.01	0.01	0.01
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.01	0.01	0.01	0.01	0.01	0.01
Non-OECD Annex I	4.12	4.12	4.12	4.12	4.12	4.12
OECD	18.36	18.36	18.36	18.36	18.36	18.36
Russian Federation	3.11	3.11	3.11	3.11	3.11	3.11
South & SE Asia	0.01	0.01	0.01	0.01	0.01	0.01
United States	8.43	8.43	8.43	8.43	8.43	8.43
World Total	22.54	22.54	22.54	22.54	22.54	22.54

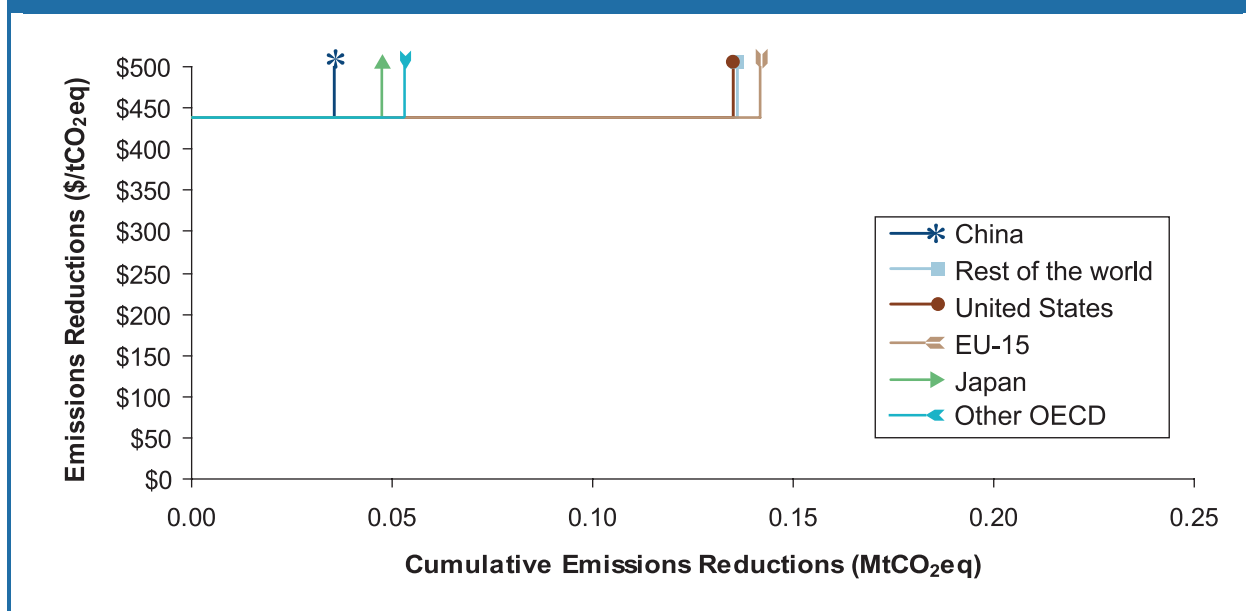
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 5-10: World Breakeven Costs and Emissions Reductions in 2020 for Aerosols^a

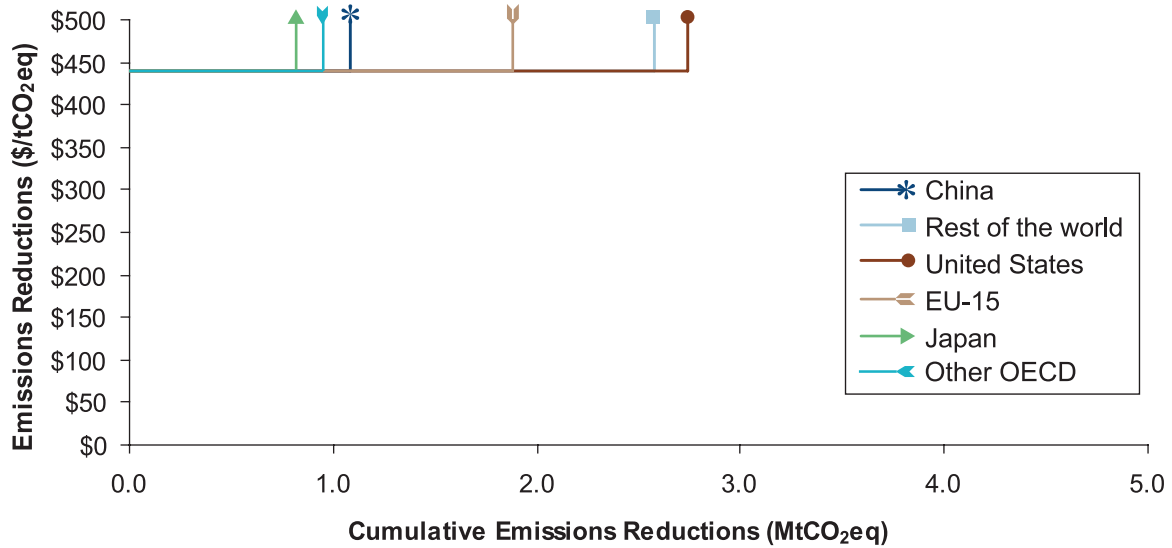
Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%	Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Cumulative Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
DPI	\$439.54	10.06	50.0%	10.06	50.0%
HFC to HC	-\$6.34	3.95	10.0%	3.95	10.0%
HFC to NIK	-\$5.87	3.95	10.0%	7.91	20.0%
HFC-134a to 152a	-\$1.07	14.64	37.0%	22.54	57.0%

^a Results are separated by the line to reflect that the MDI option addresses different baseline emissions than the non-MDI options.

Figures 5-3 and 5-4 display the MDI aerosol international marginal abatement curves by region for 2010 and 2020, respectively.

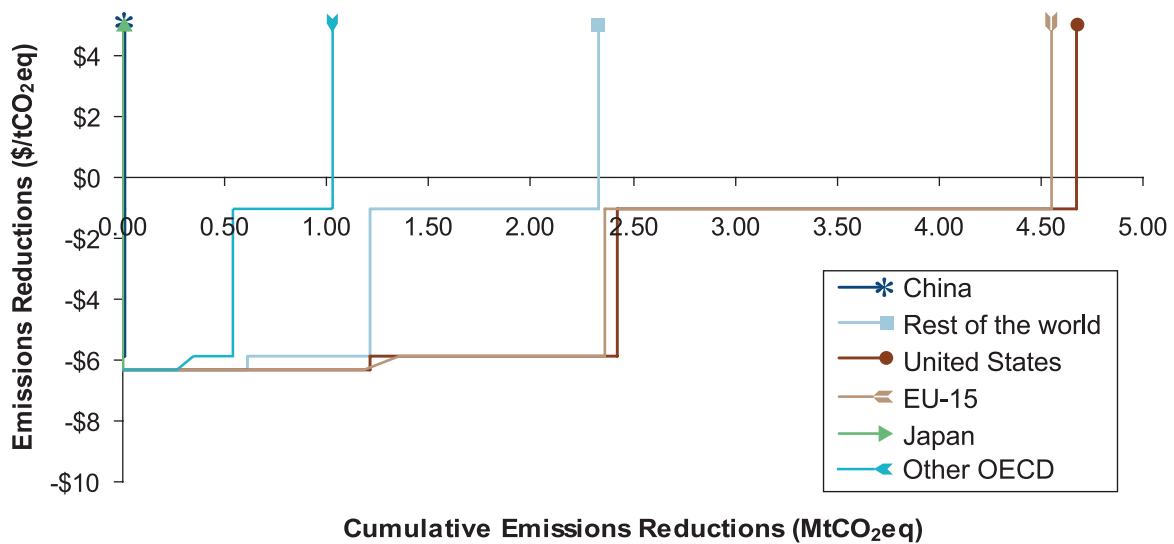
Figure 5-3: 2010 MAC for MDI Aerosols, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

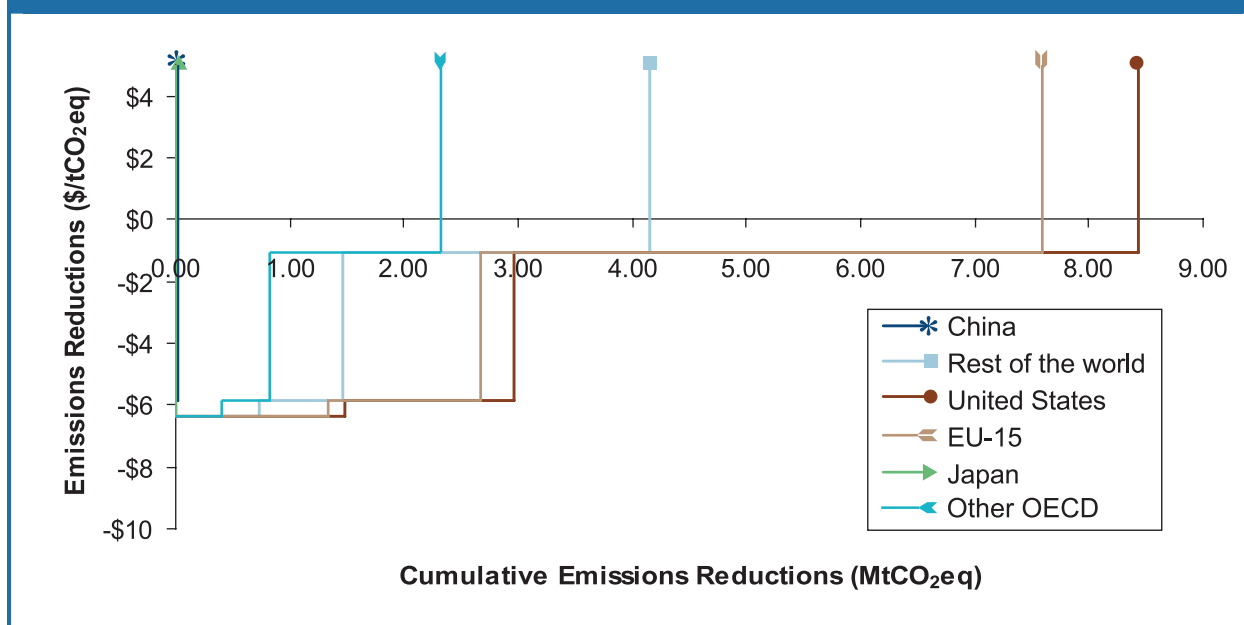
Figure 5-4: 2020 MAC for MDI Aerosols, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figures 5-5 and 5-6 display the non-MDI aerosol international MACs by region for 2010 and 2020, respectively.

Figure 5-5: 2010 MAC for Non-MDI Aerosols, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 5-6: 2020 MAC for Non-MDI Aerosols, 10% Discount Rate, 40% Tax Rate

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.5.4.2 Uncertainties and Limitations

This section focuses on the uncertainties and limitations associated with the cost estimates presented in this analysis. The significant areas of uncertainty are in how costs and the maximum market penetrations for these mitigation technologies may vary internationally. The analysis is currently limited in the lack of this specificity on region-specific cost analysis and maximum market penetration estimates. Additionally, the following uncertainties should be noted:

- **Non-MDI: Replacement with NIK Alternatives.** There is uncertainty surrounding the significant variability of one-time costs associated with the financial components of projects targeting NIK replacements for HFC-containing aerosol products. As such, the assumption used is limited to the current understanding of this variability.
- **Non-MDI: Replacement with Hydrocarbon Aerosol Propellants.** The major limitation associated with this option is regarding the annual costs. The analysis does not quantify any annual labor costs that may be incurred to ensure good handling practices of hydrocarbons (considered HAPs); regular maintenance on fire prevention devices such as fire detection systems, sprinklers, and shut-off valves; and proper safety training for employees (UNEP, 2002).

IV.5.5 Summary

This analysis considers four mitigation options: MDI replacement with DPIs, non-MDI replacement with lower GWP HFCs, non-MDI replacement with NIK alternatives, and non-MDI replacement with HC aerosol propellants. The first option has the potential to abate emissions from the MDI baseline, while the latter three options have the potential to abate emissions from the non-MDI baseline.

IV.5.5.1 MDI Aerosols

Global baseline HFC emissions from MDI aerosols are estimated to grow from 2.9 to 20.1 MtCO₂eq between 2000 and 2020. In 2020, the Annex I region is estimated to be responsible for approximately 69 percent of the baseline emissions and represents the highest emissions growth from the MDI baseline, from 2.8 MtCO₂eq in 2000 to 13.8 MtCO₂eq in 2020 (see Table 5-1).

As Table 5-10 illustrates, converting from HFC MDIs to DPIs is not a cost-effective abatement option—the estimated cost worldwide is more than \$400 dollars per tCO₂eq at a 10 percent discount rate and 40 percent tax rate—although the option may be implemented for other reasons (e.g., preferred delivery system by a pharmaceutical company). At this cost, this option could abate 50 percent of global MDI emissions, or 10.06 MtCO₂eq, annually by 2020. The costs per tCO₂eq for each region are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be performed to determine actual variability in costs across regions.

IV.5.5.2 Non-MDI Aerosols

Baseline HFC emissions from non-MDI aerosols are estimated to grow from 24.2 MtCO₂eq to 39.5 MtCO₂eq globally for the years 2000 through 2020. In 2020, the majority of emissions is from the Annex I region, which represents the highest emissions growth from the non-MDI baseline, from 24.1 MtCO₂eq in 2000 to 39.4 MtCO₂eq in 2020 (see Table 5-2).

As shown in Table 5-10, the greatest emissions reduction opportunities in all of the regions analyzed may result from converting to HC, at a cost savings of \$6.34 per tCO₂eq at a 10 percent discount rate and 40 percent tax rate. The other two options, converting to NIK and HFC-152a, also represent a cost savings of \$5.87 and \$1.07 per tCO₂eq under the same discount and tax rate scenario, respectively. Globally, 22.54 MtCO₂eq or 57 percent of global emissions from non-MDI aerosols, can be reduced in 2020 at a cost below \$0.00 per tCO₂eq. As with MDI aerosols, costs per tCO₂eq for all regions are equivalent because available data on costs for abatement technologies were not scaled to reflect potential differences in the costs internationally. Additional research may be performed to determine actual variability in costs across regions.

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IV.6 HFC Emissions from Fire Extinguishing

IV.6.1 Introduction

Fire-extinguishing applications can be divided into two categories: portable fire extinguishers (e.g., streaming applications) that originally used halon 1211 and total flooding applications that originally used halon 1301 or halon 2402 (USEPA, 2004; March Consulting Group, 1998, 1999). Historically, SF₆, another high-GWP gas, was used in select fire-extinguishing systems, such as for system discharge testing purposes by the U.S. Navy. For the most part, however, SF₆ is no longer used in any capacity in the fire-protection sector.

The principal greenhouse gases used in and emitted from the fire-extinguishing sector are hydrofluorocarbons (HFCs) (HFC-227ea, HFC-236fa, and HFC-23) and blends containing perfluoromethane (CF₄). These gases have 100-year GWPs that range from 2,900 to 11,700 (IPCC, 1996).

These high-GWP gases are substitutes for halons, ozone-depleting substances (ODSs) that have been, and in many countries still are, widely used in fire-extinguishing applications. Although halons were produced in much lower volumes than other ODSs, they have extremely high ozone depletion potentials (ODPs) because of the presence of bromine, which reacts more strongly with ozone than chlorine. Halons have been used historically in fire-suppression and explosion-protection applications because they are electrically nonconductive, dissipate rapidly without residue, are safe for limited human exposure, and are extremely efficient in extinguishing most types of fires (USEPA, 1994).

Portable fire extinguishers are most frequently used in offices, manufacturing and retail facilities, aerospace/marine applications, and homes. Market penetration of HFCs in this sector has been limited and is unlikely to grow or even keep pace with the growth in portable extinguishers (Wickham, 2003a). Perfluorocarbons (PFCs) have had a very small penetration in the portable fire extinguisher market. By 2020, only one HFC, HFC-236fa, is expected to be used to a limited extent as a halon replacement in small segments of the portable extinguisher sector. Overall, portable applications represent a much smaller share of total fire-extinguishing sector greenhouse gas emissions than do total flooding applications, and the U.S. Environmental Protection Agency (USEPA) projects that their relative share of emissions will decrease over time, based on cost reasons outlined in Wickham (2002).

The majority of HFC emissions associated with fire extinguishing come from its use as a replacement for some halon 1301 applications in the total flooding market. Total flooding systems are usually used to protect a variety of spaces, including the following:

- electronic and telecommunications equipment, such as tape storage areas, computer facilities, telecommunications gear, medical facilities, control rooms in nuclear power plants, and air traffic control towers;
- military applications, including aviation engine nacelles¹ and dry bays, naval engine compartments, and engine compartments and occupied crew spaces of ground combat vehicles;
- oil production facilities;
- flammable liquid storage areas;
- engine nacelles and cargo bays of commercial aircraft;

¹ Nacelles are enclosed engine housings.

- cultural institutions and museums;
- records storage areas;
- bank vaults;
- warehouses; and
- special facilities, such as research laboratories and military facilities.

Halon 1301 was widely used in total flooding applications because of its unique features (Wickham, 2002).² Halon 1301 is a clean agent, meaning that it does not leave residue on equipment or in the protection enclosure after discharge. In addition, halon 1301 is safe for limited, acute human exposure at the concentration used for fire extinguishing. It is also very effective at extinguishing fires and works well over a broad temperature range. Because halon 1301 was inexpensive, and design and installation of halon 1301 systems were relatively simple compared with other fire-extinguishing systems, these systems reached almost all segments of the total flooding fire-extinguishing market.

The alternatives to halon 1301 in total flooding applications can be categorized as in-kind, gaseous agent alternatives (i.e., halofluorocarbons, CO₂, inert gases, fluorinated ketones) and NIK alternatives (i.e., dispersed and condensed aerosol extinguishing systems, water sprinklers, water mist, foam,³ or inert gas generators). In most Annex I countries, halofluorocarbon HFC-227ea has emerged as the primary replacement for halon 1301 in total flooding applications that require clean agents. Other HFCs, such as HFC-23, HFC-236fa, and HFC-125, have been evaluated and determined to be safe for limited, acute human exposure but are used in smaller amounts as a result of environmental,⁴ technical, and economic concerns. For example, use of HFC-125 has been limited to normally unoccupied specialty applications, such as aviation engine nacelles. However, over the next 20 years, HFC-23 and HFC-125 are expected to only gain a strong foothold in the Russian Federation, based on confidential information collected for this report from members of UNEP's Halon Technical Options Committee (HTOC). A small number of telecommunications facilities in Eastern Europe historically used PFCs (C₃F₈ and C₄F₁₀). In the United States, PFC use in fire suppression is very limited and is expected to tail off—the U.S. manufacturer of PFCs for fire suppression withdrew these agents from the market a number of years ago because of concern about their high GWP. In addition, HCFCs have historically been used as halon 1301 replacements, particularly in Eastern and Southern Europe. Over time, the use of HCFCs and PFCs in total flooding applications is expected to be phased out and replaced primarily with HFCs, in addition to other alternatives.

Available in-kind, nonhalocarbon alternatives in total flooding applications include CO₂ systems, used primarily in marine and industrial applications; fluorinated ketones; and inert gas systems, which contain nitrogen or argon or blends of these gases, sometimes incorporating CO₂ as a third component. Inert gas systems have become the dominant halon 1301 replacement in many parts of Europe, most notably in northern European countries.

Available NIK alternatives and technologies include powdered aerosols, water sprinklers, water mist systems, foams, and combinations of these systems, such as aerosols with a halocarbon agent or water mist with a gaseous agent or with foam.

² The Russian Federation is an exception; it has historically relied on halon 2402, not halon 1301.

³ Foams can be protein based or synthetic based. Some synthetic-based foams contain fluorocarbons.

⁴ Whereas HFC-125 has a GWP of 2,800, approximately the same as HFC-227ea (GWP of 2,900), the other gases have much higher GWPs. The GWP of HFC-236fa is 6,300, and the GWP of HFC-23 is 11,700.

IV.6.2 Baseline Emissions Estimates

IV.6.2.1 Emissions Estimating Methodology

Description of Methodology

Specific information on how the emissions model was used to calculate ODS substitute emissions from all sectors producing fire-protection emissions is described below.

The USEPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of ODS substitutes (HFCs) in the United States. Emissions estimates for non-U.S. countries are derived using country-specific ODS consumption estimates, as reported under the Montreal Protocol, in conjunction with Vintaging Model output for the fire-extinguishing sector. For countries for which sufficient data were available, country-specific Vintaging Models were developed.

This analysis first incorporates estimates of the consumption of ODSs by country, as provided by UNEP (1999). Estimates for EU were provided in aggregate, and GDP was used as a proxy to distribute consumption among the individual member nations.

Emissions Equations

This analysis assumes that total emissions from leakage, accidental discharges, and fire extinguishing, in aggregate, equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, the fire-extinguishing agent is assumed to be released at a constant rate for an average equipment lifetime.

$$E_j = r \times \sum Qc_{j-i+1} \text{ for } i=1 \rightarrow k \quad (6.1)$$

where

- E = Emissions. Total emissions of a specific chemical in year j for fire-extinguishing equipment, by weight.
- r = Percentage released. Average annual percentage of the total chemical in operation that is emitted to the atmosphere.
- Qc = Quantity of chemical. Total amount of a specific chemical used in new fire-extinguishing equipment one lifetime (k) ago (e.g., j – k + 1), by weight.
- i = Counter. Runs from 1 to lifetime (k).
- j = Year of emissions.
- k = Lifetime. The average lifetime of the equipment.

Estimates used for the percentage released, *r*, and lifetime of equipment, *k*, can have a significant effect on the resulting emissions estimates. For this analysis, the U.S. Vintaging Model assumed that the percentage released, *r*, or the emissions factor, is 2 percent for both the total flooding sector (Verdonik and Robin, 2004) and the streaming sector. These estimates were chosen to account, on average, for all emissions from servicing, leaks, accidental/false discharges, system decommissioning, or intentional discharges to extinguish fires. The U.S. Vintaging Model also assumes equipment lifetime, *k*, for streaming and flooding applications to be 10 and 20 years, respectively.

Regional Variations/Adjustments

To estimate baseline emissions, information collected on current and projected market characterizations of international total flooding sectors was used to create country-specific versions of the

Vintaging Model (i.e., country-specific ODS substitution patterns). Information on the current and projected relative market size of halon substitutes was obtained for Australia, Brazil, China, India, Japan, the Russian Federation, and UK, as provided by HTOC members from those countries.⁵ General information was also collected on Northern, Southern, and Eastern Europe. For all other non-U.S. countries, baseline emissions information from some of these countries was used to adjust substitution patterns, as described below:

- Eastern Europe was used as a proxy for the countries in FSU and CEITs except the Russian Federation, where specific information was available.
- Australia was used as a proxy for New Zealand.
- Brazil was used as a proxy for countries in Latin America and the Caribbean.
- India was used as a proxy for all other developing countries.

For all other non-U.S. Annex I countries, the U.S. ODS substitution pattern was used as a proxy.⁶ In addition, an adjustment factor was applied to EU countries to account for European Regulation 2037/2000 on Substances that Deplete the Ozone Layer, which mandated the decommissioning of all halon systems and extinguishers in the EU by the end of 2003 (with the exception of those applications that are defined as critical uses) (Europa, 2003). To reflect this, the methodology assumes that all halon systems in the EU were decommissioned by 2004.⁷

IV.6.2.2 Baseline Emissions

The resulting baseline estimates of GWP-weighted HFC emissions developed for this report are summarized in Table 6-1 and Figure 6-1. Baseline emissions estimates are presented in million metric tons of carbon dioxide equivalents (MtCO₂eq). The estimates of the global total flooding fire-protection market developed for this report are generally consistent with those in the Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP) (1999) report, which estimated that in the late 1990s, between 20 percent and 22 percent of systems that would formerly have used halons used HFCs, and that less than 1 percent used PFCs.

⁵ Fire-protection experts in these countries provided confidential information on the status of national halon transition markets and average costs to install the substitute extinguishing systems in use (on a per volume of protected space basis) for 2001 through 2020.

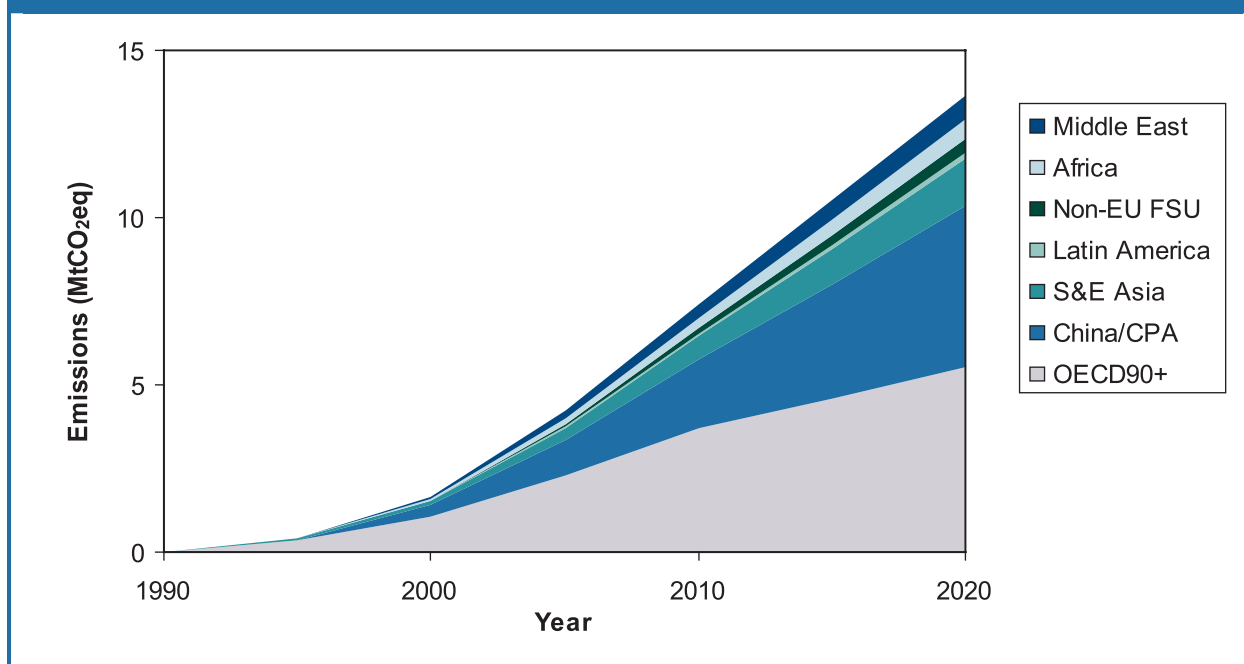
⁶ This analysis assumes that, of the new total flooding protection systems in which halons have been previously used in the United States, the market is currently made up of approximately 16 percent HFC-227ea, less than 1 percent HFC-23, 10 percent inert gas, and 74 percent other NIK agents.

⁷ The use of halon in marine applications is unlikely to have met the 2004 phaseout deadline because these applications are also governed by regulations issued by the International Maritime Organization (IMO) and because many EU ships contained halon 1301 fire-suppression systems. However, because of a lack of available data on emissions from marine-based fire-protection systems as a percentage of the total EU fire-extinguishing sector, this analysis simply assumes full compliance with the EU regulation.

Table 6-1: Total Baseline HFC Emissions from Fire Extinguishing (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	0.1	0.3	0.6
Annex I	1.1	3.8	5.8
Australia/New Zealand	0.0	0.1	0.1
Brazil	0.0	0.0	0.0
China	0.3	2.0	4.9
Eastern Europe	0.0	0.0	0.1
EU-15	0.1	1.2	2.2
India	0.0	0.0	0.1
Japan	0.1	0.6	0.9
Mexico	0.0	0.0	0.1
Non-OECD Annex I	0.0	0.1	0.3
OECD	1.1	4.1	6.3
Russian Federation	0.0	0.1	0.3
South & SE Asia	0.0	0.3	0.5
United States	0.7	1.6	1.9
World Total	1.7	7.4	13.7

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Figure 6-1: Baseline HFC Emissions from Fire Extinguishing by Region (MtCO₂eq)

CPA = Centrally Planned Asia; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development.

This analysis assumes that systems designed to protect against Class A surface fire hazards represent an estimated 95 percent of the total flooding sector in all countries, and that the remaining 5 percent of the applications are designed to protect against Class B fire hazards (flammable liquids and gases).⁸ According to projected global average emissions estimates, emissions from systems that protect against Class A fire hazards will account for approximately 74 percent of the global total fire-extinguishing sector in 2005, 79 percent in 2010, 85 percent in 2015, and 87 percent in 2020. Table 6-2 presents the estimated global average breakout of total fire-sector HFC emissions by application, as estimated by the USEPA's Vintaging Model. This assumed breakout was used to estimate the emissions reduction potential of the abatement options applicable to Class A or Class B total flooding sectors for all regions.

Table 6-2: Assumed Breakout of Total GWP-Weighted Baseline Fire-Extinguishing Emissions (Percent)

	Annex I and Non-Annex I Countries			
	2005	2010	2015	2020
Flooding	78.0%	83.1%	89.5%	92.0%
Class A emissions (95% total flooding)	74.1%	78.9%	85.0%	87.4%
Class B emissions (5% total flooding)	3.9%	4.2%	4.5%	4.6%
Streaming	22.0%	16.9%	10.5%	8.0%
Total	100.0%	100.0%	100.0%	100.0%

Note: Totals may not sum because of independent rounding.

IV.6.3 Cost of HFC Emissions Reductions from Fire Extinguishing

This section presents a cost analysis for achieving HFC emissions reductions from the baselines presented in Table 6-1. Each abatement option is described below, but costs are analyzed for only those options not assumed to occur in the baseline (or for which a larger market penetration than reflected in the baseline is believed to be possible) and for which adequate cost data are available. All cost analyses assume a 20-year project lifetime. To the extent possible, this analysis considered total equivalent warming impacts (TEWI) to account for the cost and greenhouse gas-emissions impacts of energy consumption (i.e., indirect emissions) associated with the heating/cooling of additional space needed to house alternative agents. However, because of data limitations, a full life-cycle analysis was not possible. For example, the cost and emissions impacts associated with manufacturing alternative agents and all system components were not assessed in this analysis, although they may potentially be significant.

IV.6.3.1 Description and Cost Analysis of Abatement Options

Because streaming applications account for a relatively small proportion of fluorocarbon use (e.g., HFC-236fa) in fire extinguishing, this cost analysis focuses only on abatement options for the total

⁸ Wickham (2002) estimates that over 90 percent of the halon 1301 systems ever installed in the United States were designed to protect against hazards where the anticipated fire type was primarily Class A in nature, and that approximately 10 percent of the U.S. applications served by halon 1301 had hazardous materials of the Class B type. However, because much of the former halon 1301 Class B applications have been replaced by non-HFC alternatives (e.g., carbon dioxide), this analysis assumes that only 5 percent of HFC emissions from the total flooding sector are from Class B applications, and that the remaining 95 percent are from Class A applications.

flooding sector.⁹ In 2005, the majority of emissions from the fire-extinguishing sector are expected to have resulted from leaks and discharges (both accidental and intended use to extinguish fires) from total flooding applications. The options for reducing HFC emissions from the fire-protection sector include the use of alternative fire-protection agents and the use of alternative technologies and practices. Eight potential options are identified, but only the first three are explored further in the cost analysis:

- inert gas,
- water mist,
- fluorinated ketone (FK-5-1-12),
- carbon dioxide,
- recovery and reuse of HFCs,
- improved detection systems,
- fine aerosols, and
- inert gas generators.

As described further below, available alternatives to reduce emissions in the fire-protection sector may not be technically or economically viable for all end-use applications. For example, military applications often have specialized needs that do not exist in other end-use applications. Applications that are space and/or weight constrained, such as marine and aviation applications, are more limited in their choice of agents. Electronic and telecommunication applications, which represent the largest use of HFCs in the total flooding sector, offer the greatest opportunities to apply alternatives, although some economic penalties and technical challenges may exist.

The remainder of this section provides an overview of each abatement option—inert gas, water mist, and fluorinated ketone—and presents the assumptions and results of cost analyses. For reasons discussed further below, these options are assumed to be applicable only to new (not existing) total flooding systems, where “new” is defined as systems installed in 2005 or later. All costs are presented in 2000 dollars. A detailed description of the cost and emissions reduction analysis for each option can be found in Appendix J for this chapter.

Inert Gas Systems

Inert gas systems extinguish fires using argon, nitrogen, or a blend of the two, sometimes incorporating CO₂ as a third component (UNEP, 2001). Inert gas systems provide both fire protection and life safety/health protection equivalent to HFCs in most Class A (ordinary combustible) fire hazards, including electronics and telecommunications applications.

Although inert gas systems are effective at extinguishing fires, their discharge time is slower than that of HFC systems—60 seconds or more compared with 10 to 15 seconds (Kucnerowicz-Polak, 2002). In areas where a rapidly developing fire is likely, inert gas systems are not recommended (UNEP, 2001; Kucnerowicz-Polak, 2002). Improved devices that recognize and extinguish fires before they have a chance to spread may help alleviate these concerns. Another limitation is that inert gas systems need a larger volume of agent to extinguish fires than do HFC systems. The weight-support structures and space

⁹ The USEPA estimates that more than 90 percent of the halon replacement market in the streaming sector currently consists of NIK alternatives, while HFCs account for less than 5 percent of this market. By 2020, the USEPA projects that HFCs will account for an even smaller portion of the halon replacement market in the streaming sector. It is expected that the high cost of HFCs will ensure that they are used only where they are absolutely needed (i.e., in areas where cleanliness is an absolute necessity) (Wickham, 2002).

needed for additional steel cylinders of gas may prohibit the retrofit of many existing HFC systems, such as those on small ships and in other applications where the system infrastructure is fixed. Extra storage space for cylinders may also mean extra space to heat and cool, which means more expense and energy consumption.

This analysis assumes inert gas systems are technically applicable¹⁰ to emissions from total flooding systems designed for Class A fires. Because of the additional space requirements associated with inert gas systems, it is not assumed to be economically feasible to retrofit existing HFC Class A fire-extinguishing systems to this option. This analysis therefore assumes that this option is applicable only to new Class A applications (i.e., those installed in 2005 or later). Because of the additional space and weight requirements and the slower discharge times, market penetration rates reflect the assumption that this option cannot fully displace HFC use in new Class A total flooding applications. Furthermore, because this option entails additional costs (see discussion below), market penetration in non-Annex I countries is assumed to be 50 percent less than in Annex I countries for all years because of economic challenges faced by developing countries. Table 6-4 (Annex I countries) and Table 6-5 (non-Annex I countries) present the assumed market penetration rates of inert gas systems into new systems and as a percentage of total sector baseline emissions.

Water Mist Systems

Water mist systems use relatively small droplet sprays under low, medium, or high pressure to extinguish fires. These systems use specially designed nozzles to produce much smaller droplets than are produced by traditional water-spray systems or conventional sprinklers, so they use less water to extinguish a fire (UNEP, 2001; Wickham, 2002). Another benefit of water mist systems is that, in some applications (e.g., marine applications), they can be brought into action faster than HFC systems because there is less concern about applying water mist in situations where openings to the space are not all closed—which in turn leads to reduced fire damage. In addition, unlike HFC systems, which are usually limited to a single discharge of agent, most water mist systems have an unlimited water supply in land-based operations, and at least 30 minutes of potable water discharge followed by an unlimited amount of seawater for marine applications (Wickham, 2003b).

To date, water mist systems have been used in shipboard accommodation, storage and machinery spaces, combustion turbine enclosures, flammable and combustible liquid machinery applications, and light and ordinary hazard sprinkler applications (UNEP, 2001). Water mist systems can provide equivalent fire protection and life safety/health protection for Class B fuel hazards, where low-temperature freezing is not a concern. Systems designed to protect against Class B (flammable liquid) fire hazards are estimated to account for approximately 5 percent of the HFC total flooding market in the United States and were assumed to account for the same percentage in all non-U.S. countries (Wickham, 2002). Water mist systems have also found acceptance in Class A applications but as replacements for water sprinklers, not HFCs. Therefore, this report does not consider water mist as an option for abating HFC emissions from Class A applications.

Some barriers have impeded broad use of water mist systems. First, these systems have not proven effective in extinguishing small fires in spaces with volumes greater than 2,000 cubic meters (IMO, 2001;

¹⁰ In this report, the term “technically applicable” refers to the emissions to which an option can be theoretically applied. Because inert gas systems are assumed to be used only in Class A fire total flooding applications, the technical applicability is 100 percent of the emissions associated with those types of systems. Other factors will affect the application of the option, for example to new or existing systems, and the market penetration assumed in this analysis.

Wickham, 2002). Additionally, because there is a nonlinear relationship between the volume of space and the amount of water mist needed to extinguish a given fire, and because this relationship (referred to as the “mechanism of extinguishment”) is not well understood, applications of water mist systems have been limited to those where fire test protocols have been developed, based on empirically tested system performance. Therefore, new applications may require empirical performance testing prior to installing such systems to ensure safety and obtain approval of the proper regulatory or standard-setting authority. Currently, an IMO working group is studying this situation and considering proposals that suggest an overhaul to the test methods and approval guidelines. Should IMO change its water mist requirements to something more flexible regarding the extinguishing of small fires in these sized spaces, it will make a difference in the future cost and, thus, market acceptance of water mist systems (Wickham, 2003b). In addition, the use of additives—such as salts or foam or a combination of these systems with gaseous agents—offers other options under investigation to improve system performance for specific applications. Many researchers and industry experts believe that solutions to these market barriers are well within reach (Wickham, 2002).

Other market barriers for this option include additional space requirements for system storage compared with conventional HFC-227ea systems. Indeed, water mist systems require an estimated seven times more space than HFC-227ea (Wickham, 2003b). In addition, water mist systems used in marine applications are cost prohibitive for protecting spaces less than 3,000 cubic meters in size.¹¹

This analysis assumes that water mist systems are technically applicable to the emissions from total flooding systems designed to protect against Class B fires. Because of the additional space requirements associated with this option, it is assumed that water mist systems could not feasibly replace any existing HFC systems in Class B fire-protection applications and, therefore, are used only in new Class B total flooding applications (i.e., those installed in 2005 or later).

This analysis assumes that the remaining technical constraints associated with water mist systems will gradually be overcome and that by 2020, in Annex I countries, water mist systems will reach full market penetration in all new Class B fire-suppression systems used to protect large spaces. Market penetration estimates for non-Annex I countries are assumed to be 50 percent less than those for developed countries, as a result of economic considerations. Table 6-3 and Table 6-4 present the maximum market penetrations assumed for this option.

Fluorinated Ketone (FK-5-1-12)

FK-5-1-12-mmy2 (also known as 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, and commonly referred to as FK-5-1-12) is a fluorinated ketone with an atmospheric lifetime up to 2 weeks and a 100-year GWP of approximately 1 (ICF Consulting, 2003). This alternative received the USEPA’s Significant New Alternatives Policy (SNAP) approval as an acceptable replacement for halon 1301 in flooding applications at the end of 2002, and for halon 1211 in nonresidential streaming applications in early 2003.

Compared with HFC-227ea total flooding systems, FK-5-1-12 systems are associated with slight space and weight penalties; when averaged across different-sized spaces, space penalties are on the order of 7

¹¹ This cost information is based on water mist systems employed under the current IMO requirements for marine systems, which are much more severe than the requirements for land-based systems. The use of water mist systems in nonmarine applications appears to be more cost competitive with other alternatives (Wickham, 2003a).

percent,¹² and weight penalties are approximately 17 percent—which could make its use in confined spaces (e.g., ships, aircraft) less attractive, although some marine installations have already been reported (Werner, 2004a).¹³ Moreover, because of its cost (see cost analysis below) and its relatively recent entry¹⁴ into this market, the extent of future commercial use of this option is not known.

Although this option is not associated with major floor space penalties and appears not to suffer from any significant technical barriers, it is only assumed to be technically applicable in new Class A flooding applications (i.e., those installed in 2005 or later), because the cost analysis does not assess retrofit costs. Table 6-4 and Table 6-5 present the incremental maximum market penetration assumptions for this option, which project that this option will gain a foothold in the marketplace and after 2010 will out-compete inert gas systems in new Class A total flooding applications. Because of the reasons outlined above, this analysis conservatively assumes that market penetration will be low in early years, although others project higher sales (Werner, 2004b). Market penetration is assumed to be greater in Annex I countries than in non-Annex I countries because of economic considerations.

Carbon Dioxide

CO₂ has been used for many decades in total flooding systems. Some of the hazards and equipment that CO₂ systems protect are flammable liquid materials; electrical hazards such as transformers, switches, circuit breakers, rotating equipment, and electronic equipment; engines using gasoline and other flammable liquid fuels; ordinary combustibles such as paper, wood, and textiles; and hazardous solids (NFPA, 2000). Because of the lethal concentrations at which CO₂ is required for use as a fire-extinguishing agent, there have been concerns about incidences of deaths and injuries attributed to exposure to this agent (USEPA, 2000; Wickham, 2003b). In 2003, the NFPA Technical Committee on NFPA 12: Standard for Carbon Dioxide Fire Extinguishing Systems reviewed a proposal to change the standard to prohibit use of these systems in normally occupied areas (Wickham, 2003b). The IMO's Safety of Life at Sea (SOLAS) standard does not prohibit the use of CO₂ in normally occupied areas but calls for the use of suitable alarms and mandates against the use of automatic release of the fire-extinguishing medium, as noted in *Carbon Dioxide as a Fire Suppressant: Examining the Risks* (USEPA, 2000). IMO has also considered whether to prohibit use of CO₂ systems in occupied areas as part of that organization's broad review of the current performance testing requirements for all shipboard fire-extinguishing systems (IMO, 2003; Wickham, 2003b).

As one of the oldest fire-extinguishing agents in use, and as a more economical option than HFCs, CO₂ has developed its own niche market in narrow-use total flooding applications. Whereas CO₂ could and does replace some halon use where permitted by regulations, this analysis assumes that CO₂ would be selected as a first-choice replacement of halon, not as a second transition, after more costly HFCs. For example, the majority of U.S. ship owners have shifted from halon 1301 to CO₂ for mandatory engine room protection for new ships (Wickham, 2002). For this reason, any use of CO₂ is assumed to occur in the baseline and not as an option to replace HFC systems. It is therefore not considered in the cost analysis.

¹² Smaller spaces actually have no footprint penalty, but larger spaces (approximately equal to or greater than 1,000 cubic meters) have space penalties of roughly 14 percent.

¹³ It has been reported that the space penalty is only associated with use in large systems, and that the weight penalty has not proven to be an impediment (Werner, 2004b).

¹⁴ This agent is in the 2004 edition of the National Fire Protection Association (NFPA) Standard on Clean Agent Fire Extinguishing Systems (NFPA, 2004) and has been accepted for future addition to the International Standards Organization (ISO) International Standard on Gaseous Fire-Extinguishing Systems (Wickham, 2003a).

Recovery and Reuse of HFCs

HFCs can be recovered for reuse at service and decommissioning. For several reasons, however, this analysis does not incorporate this option into the cost analysis. First, responsible halon management practices are assumed to be a standard convention in fire protection throughout the world.¹⁵ Second, given the high costs of HFCs, there is a strong financial incentive for maximum recovery following the decommissioning of large HFC systems. Most HFC systems—with lifetimes ranging from 10 to 20 years—have not yet reached the end of their useful lifetimes and, therefore, wide-scale system recovery and recycling at decommissioning has not yet occurred; this analysis assumes that such practices will occur in the baseline.

Improved Detection Systems

One effective way of reducing HFC emissions from the fire-extinguishing sector is to install improved detection and control systems to prevent a false discharge (e.g., high-sensitivity smoke detection systems that provide early warning to preempt the need for actual system discharge) or minimize the amount of agent discharged to extinguish a fire.

Since advanced detection systems have been available for the last decade or so, this analysis assumes that total flooding HFC systems have been and are being equipped with such systems internationally. Because improved detection systems are assumed to be used in the baseline, this option is not considered in the cost analysis.

Fine Aerosols

Aerosols are being developed for use as extinguishing agents in niche markets in the United States, such as aerospace, marine, and some military applications. The NFPA has written a draft standard (*NFPA 2010*) for this agent (NFPA, 2003). It is possible that if fine aerosols are ever successfully brought to market, it may be applicable in other end-uses (Wickham, 2002).

Because fine aerosols are not currently a viable commercial alternative to HFCs in fire protection, and much uncertainty exists as to whether the associated technical and economic barriers will be overcome to enable them to become a viable option, fine aerosols are not considered in the cost analysis.

Inert Gas Generators

Inert gas generators use a solid material that oxidizes rapidly, producing large quantities of CO₂ and/or nitrogen. Although this technology has demonstrated space and weight requirements equivalent to halon 1301, it has thus far been used only in specialized applications in the United States (e.g., dry bays on military aircraft) (Wickham, 2002). Because of insufficient data on these systems and the uncertainty associated with their applicability in other fire-extinguishing applications, this option is not considered in the cost analysis.

¹⁵ Responsible use practices are currently being developed and endorsed worldwide. For example, the Halon Recycling Corporation (HRC) published a *Code of Practice for Halon Reclaiming Companies* (HRC, n.d.). Because the equipment and training needed to reclaim halons are also required to reclaim HFCs, the HRC *Code of Practice* establishes the necessary infrastructure and sets the practice of reclamation as the norm for how business is done in the fire-protection industry. Although the HRC is a U.S. association, its membership consists of multinational corporations operating throughout the world. Similarly, the Halon Alternatives Research Corporation (HARC), the USEPA, and other organizations have recently developed and endorsed the *Voluntary Code of Practice for the Reduction of Emissions of HFC and PFC Fire Protection Agents* (VCOP) (Cortina, n.d.). This VCOP will also have international reach because HARC members include multinational companies in the alternative agent manufacturing, equipment manufacturing, and distribution sectors.

IV.6.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 6-3 summarizes the technical applicability of each option, which is equal to the estimated global average breakout of total fire sector HFC emissions for the application (i.e., total flooding, Class A or B) addressed by the option. Technical applicability is used in conjunction with market penetration assumptions to develop the emissions reduction potentials for each option, as explained further below. Table 6-4 provides the assumptions on maximum market penetration into annual installations of total flooding systems designed for the particular application (i.e., Class A or B fires) for each option in 2005, 2010, 2015, and 2020. Market penetrations were developed separately for Annex I and non-Annex I countries to best reflect region-specific qualitative information and possible future action. Table 6-5 presents the final maximum penetration into the installed base of equipment, taking into account the percentage of each applicable fire hazard market that is new (i.e., systems installed in 2005 or later) in all preceding years. Values from Table 6-5 are multiplied by technical applicabilities from Table 6-3 to generate the percentage reduction off baseline emissions, as presented in Table 6-6.

Table 6-3: Summary of Technical Applicability of Abatement Options (Percent)

Abatement Option	Annex I and Non-Annex I Countries			
	2005	2010	2015	2020
Inert gas (Class A flooding)	74.1%	78.9%	85.0%	87.4%
Water mist (Class B flooding)	3.9%	4.2%	4.5%	4.6%
FK-5-1-12 (Class A flooding)	74.1%	78.9%	85.0%	87.4%

Note: Values are expressed as a percentage of total fire-extinguishing emissions.

To calculate the percentage of emissions reductions off the total fire-extinguishing baseline for each abatement option, the technical applicability (from Table 6-3) was multiplied by the market penetration values (from Table 6-5), given that the reduction efficiency is 100 percent for each option. For example, to determine the percentage reduction off the 2020 baseline for FK-5-1-12 in the United States (or other Annex I countries), the following calculation was used:

$$\begin{aligned} \text{Technical applicability} \times \text{Incremental maximum market penetration} &= & (6.2) \\ 87.4\% \times 23.1\% &\approx 20.2\% \end{aligned}$$

Thus, using the assumptions in this analysis, FK-5-1-12 could reduce approximately one fifth of the Annex I 2020 emissions baseline. This figure, along with the other projected emissions reductions, is shown in Table 6-6.

Table 6-7 summarizes the cost assumptions used for the fire options presented in the discussions above.

Table 6-4: Assumed Incremental Market Penetration of Abatement Options into Newly Installed Class A or Class B Extinguishing Systems, Expressed as a Percentage of Emissions from All New Equipment

Abatement Option	Annex I Countries				Non-Annex I Countries ^a				Considerations/Rationale
	2005	2010	2015	2020	2005	2010	2015	2020	
Inert gas (New Class A)	10%	20%	30%	30%	5%	10%	15%	15%	<ul style="list-style-type: none"> Can displace HFCs in new Class A applications Additional space and weight requirements Slower discharge times Higher costs compared with baseline HFC-227ea systems lead to lower market penetration in developing countries
Water mist (New Class B)	25%	50%	75%	100%	13%	25%	38%	50%	
FK-5-1-12 (New Class A)	4%	20%	40%	50%	2%	10%	20%	25%	

^a To account for economic considerations, assumed market penetration values in developing countries are half of those assumed for developed countries.

Table 6-5: Market Penetration of Abatement Options into Newly Installed Class A or Class B Extinguishing Systems, Expressed as a Percentage of Total Sector Emissions

Abatement Option	Annex I Countries				Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020
Inert gas (Class A)	0.5%	4.5%	11.0%	18.5%	0.3%	2.3%	5.5%	9.3%
Water mist (Class B)	1.3%	11.3%	27.5%	50.0%	0.7%	5.7%	13.9%	25.2%
FK-5-1-12 (Class A)	0.2%	3.6%	11.6%	23.1%	0.1%	1.8%	5.8%	11.6%

Note: Values are expressed as a percentage of technical applicability (i.e., both new and existing Class A or Class B emissions).

Table 6-6: Percentage of Emissions Reductions Off Total Fire-Extinguishing Baseline

Abatement Option	Annex I Countries				Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020
Inert gas	0.4%	3.6%	9.3%	16.2%	0.2%	1.8%	4.7%	8.1%
Water mist	0.0%	0.5%	1.2%	2.3%	0.0%	0.2%	0.6%	1.2%
FK-5-1-12	0.1%	2.8%	9.9%	20.2%	0.1%	1.4%	4.9%	10.1%

Table 6-7: Summary of Abatement Option Cost Assumptions (2000\$)

Option	Time Horizon (Years)	U.S. One-Time Cost	U.S. Annual Costs	U.S. Annual Savings	Net U.S. Annual Costs
Inert gases	20	\$9.07 ^a	\$0.18 ^b	\$0.35 ^c	–\$0.17
Water mist	20	\$10.89 ^d	\$0.38 ^b	\$0.35 ^c	\$0.03
FK-5-1-12	20	\$7.50 ^e	\$0.50 ^b	\$0.35 ^c	\$0.15

Note: All costs are per cubic meter of protected space.

- ^a This one-time cost includes an incremental capital cost and an incremental construction cost (to build additional space). Incremental capital costs were assumed to be 10 percent greater in non-Annex I (developing) countries than in the United States and 10 percent less in Japan. In all other Annex I countries, capital costs were assumed to be the same as in the United States. No regional adjustments were made to incremental construction costs.
- ^b This cost is associated with additional heating and cooling costs. For all other countries, this annual cost was adjusted by average country-specific electricity prices (average of 1994–1999) based on *Annual Energy Outlook 2000 (Electricity Prices for Industry 1994–1999)* (USEIA, (2000).
- ^c Annual savings were assumed to result from avoided HFC-227ea emissions and associated replacement costs. No adjustments were assumed for other countries.
- ^d This one-time cost includes an incremental capital cost and an incremental construction cost (to build additional space). Capital costs were assumed to be the same in all other Annex I countries and 10 percent higher in all developing countries. No regional adjustments were made to incremental construction costs.
- ^e This one-time cost includes an incremental capital cost and an incremental construction cost (to build additional space). No regional cost adjustments were made.

IV.6.4 Results

IV.6.4.1 Data Tables and Graphs

Table 6-8 (2010) and Table 6-9 (2020) provide a summary of the potential emissions reductions at various breakeven costs by country/region. The costs to reduce 1 tCO₂eq are presented for a 10 percent discount rate and 40 percent tax rate. Table 6-10 presents the potential emissions reduction opportunities and associated annualized costs for the world in 2020. The results are ordered by increasing costs per tCO₂eq, using the highest cost in the region under the 10 percent discount rate/40 percent tax rate. Because many of the options analyzed affect indirect (CO₂ from energy generation for heating/cooling) emissions, the net (HFC + CO₂) emissions reduced by each option are presented. The direct (HFC) emissions reduced by the option and a cumulative total of emissions reduced, in MtCO₂eq and percentage of the regional fire-extinguishing baseline, are also presented.

Table 6-8: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Fire Extinguishing at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.01	0.01
Annex I	0.00	0.00	0.00	0.22	0.26	0.26
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.00	0.07	0.07	0.07
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.00	0.00	0.07	0.08	0.08
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.00	0.00	0.02	0.04	0.04
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	0.00	0.00	0.01	0.01	0.01
OECD	0.00	0.00	0.00	0.23	0.26	0.27
Russian Federation	0.00	0.00	0.00	0.01	0.01	0.01
South & SE Asia	0.00	0.00	0.00	0.01	0.01	0.01
United States	0.00	0.00	0.00	0.11	0.11	0.11
World Total	0.00	0.00	0.00	0.33	0.37	0.39

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 6-9: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Fire Extinguishing at 10% Discount Rate, 40% Tax Rate (\$/tCO₂eq)

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.06	0.11	0.12
Annex I	0.00	0.00	0.00	1.97	2.19	2.25
Australia/New Zealand	0.00	0.00	0.00	0.04	0.04	0.04
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.00	0.88	0.88	0.94
Eastern Europe	0.00	0.00	0.00	0.04	0.04	0.04
EU-15	0.00	0.00	0.00	0.79	0.81	0.84
India	0.00	0.00	0.00	0.01	0.02	0.02
Japan	0.00	0.00	0.00	0.19	0.34	0.36
Mexico	0.00	0.00	0.00	0.01	0.01	0.01
Non-OECD Annex I	0.00	0.00	0.00	0.12	0.13	0.13
OECD	0.00	0.00	0.00	2.00	2.22	2.29
Russian Federation	0.00	0.00	0.00	0.11	0.12	0.12
South & SE Asia	0.00	0.00	0.00	0.10	0.10	0.11
United States	0.00	0.00	0.00	0.70	0.74	0.74
World Total	0.00	0.00	0.00	3.30	3.62	3.77

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

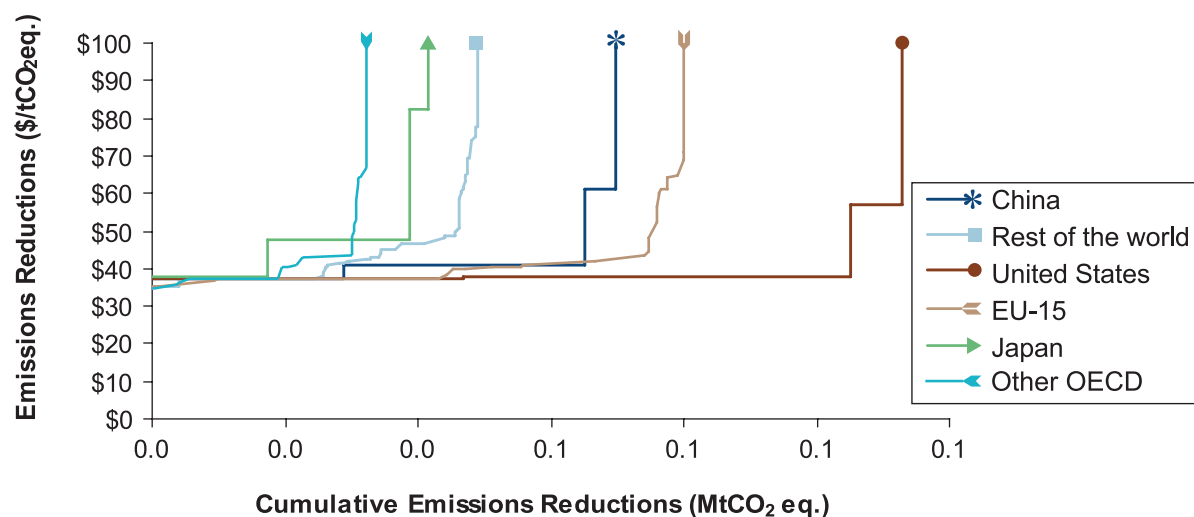
Table 6-10: World Breakeven Costs and Emissions Reductions in 2020 for Fire Extinguishing

Reduction Option	Cost (2000\$/tCO ₂ eq) DR = 10%, TR=40%		Direct Emissions Reduction ^a (MtCO ₂ eq)	Indirect Emissions Impact ^b (MtCO ₂ eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO ₂ eq)	Cum. % Reduction from 2020 Baseline
	Low	High					
FK-5-1-12	\$37.26	\$37.58	1.97	0.00	14.4%	1.97	14.4%
Inert gases	\$34.53	\$48.85	1.58	-0.11	11.5%	3.55	25.9%
Water mist	\$48.16	\$82.40	0.23	-0.04	1.6%	3.77	27.6%

^a Direct reductions refer to HFC emissions reductions (off the baseline).^b Indirect emissions impacts are those associated with energy consumption (not included in the baseline).

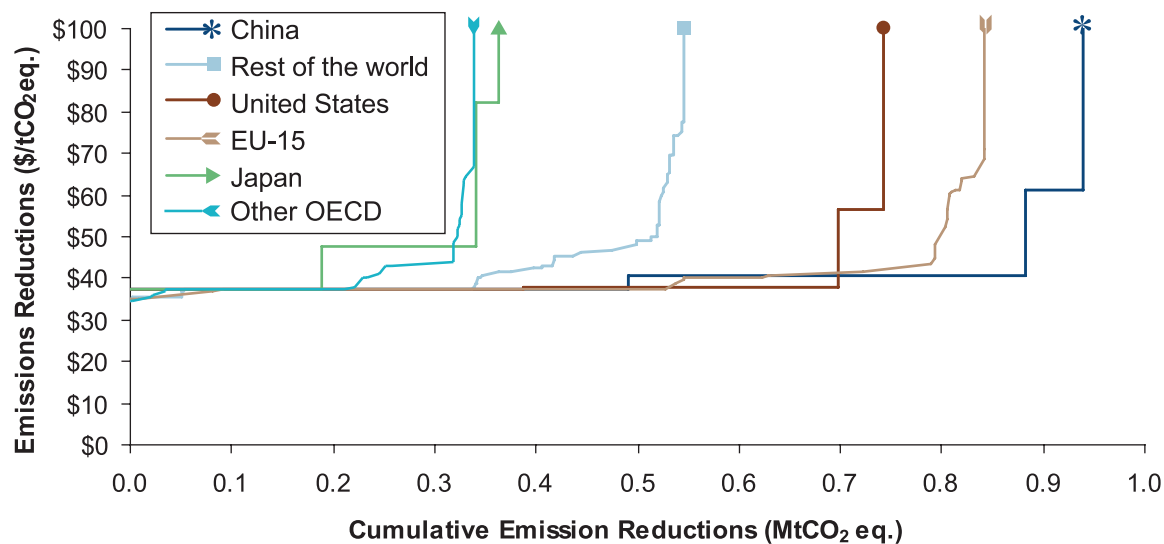
Figures 6-2 (2010) and 6-3 (2020) present MACs for this sector at 10 percent discount rates and 40 percent tax rates.

Figure 6-2: 2010 MAC for Fire Extinguishing, 10% Discount Rate, 40% Tax Rate



EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 6-3: 2020 MAC for Fire Extinguishing, 10% Discount Rate, 40% Tax Rate



EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.6.4.2 Uncertainties and Limitations

This section focuses on the uncertainties and limitations associated with the cost estimates presented in this analysis. One area of uncertainty is in how capital costs for these mitigation technologies may vary internationally, given that estimates were available only for several countries, and only for two of the three options assessed (water mist and inert gas). The analysis of the FK-5-1-12 option is currently limited in the lack of this specificity on region-specific cost analysis estimates. In addition, it should be noted that the global implementation of each option through 2020 is based on information currently available and expert opinion. Great uncertainty is associated with future projections of market behavior.

IV.6.5 Summary

Baseline HFC emissions from fire extinguishing are estimated to grow between 2005 and 2020, with the highest emissions growth expected to occur in non-Annex I countries. It is estimated that the vast majority of these emissions will come from total flooding applications; only a minor amount will come from streaming applications. Several alternatives to ozone-depleting halon 1301 for total flooding applications exist, including gaseous alternatives such as HFCs, carbon dioxide, inert gases, and fluorinated ketones, as well as NIK alternatives such as dispersed and condensed aerosol systems, water sprinklers, water mist, foam, and inert gas generators.

This analysis reviewed these alternatives and analyzed in detail three mitigation options for total flooding fire-extinguishing applications: substituting HFC systems used in new systems designed to protect against Class A fire hazards with inert gas systems, substituting HFCs used in new systems designed to protect against Class B fire hazards with water mist systems, and substituting HFC systems used in new systems designed to protect against Class A fire hazards with FK-5-1-12 systems. Inert gas and FK-5-1-12 systems may offer good opportunities to reduce emissions in total flooding applications globally. Water mist systems also have the potential to reduce global emissions from this sector, but to a lesser extent, because they are applicable only to Class B fire hazards.

This analysis demonstrates that there is a portfolio of alternatives to HFCs in the total flooding sector that can be employed to reduce HFC use and associated emissions. These alternatives include FK-5-1-12, inert gases, water mist, and other agents and systems discussed qualitatively in this report. The global implementation of each option through 2020 is based on a “best-guess” scenario. With more data, these forecasts can be improved.

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IV.7 PFC Emissions from Aluminum Production

The primary aluminum production industry is currently the largest source of PFC emissions globally. During the aluminum smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur. These are termed “anode effects” (AEs). Anode effects produce CF_4 and C_2F_6 emissions when carbon from the anode and fluorine from the dissociated molten cryolite bath combine. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects; the more frequent and long-lasting the anode effects, the greater the emissions. This report presents two baselines for PFC emissions from primary aluminum production: the technology-adoption baseline and the no-action baseline (Tables 7-1 and 7-2).

IV.7.1 Technology-Adoption Baseline

Under the technology-adoption baseline scenario, it is assumed that aluminum producers will continue to introduce technologies and practices aimed at reducing PFC emissions. It is assumed that under the technology-adoption scenario, global aluminum producers, in accordance with International Aluminum Institute (IAI) PFC emissions reduction commitments, will reduce their PFC emissions intensity (i.e., PFC emissions per ton of produced aluminum) by 80 percent from 1990 levels by 2010. This reduction can be achieved by retrofitting smelters with emissions-reducing technologies such as computer control systems and point feeding systems, by shifting production to Point-Feed Prebake (PFPB) technology, and by adopting management and work practices aimed at reducing PFC emissions.

Five different electrolytic cell types are used to produce aluminum: Vertical Stud Soderberg (VSS), Horizontal Stud Soderberg (HSS), Side-Worked Prebake (SWPB), Center-Worked Prebake (CWPB), and PFPB, which is considered the most technologically advanced process to produce aluminum. Although PFPB systems can be improved through the implementation of management and work practices, as well as improved control software, the analysis assumes that retrofit abatement options will occur only on existing VSS, HSS, SWPB, and CWPB cells.

Figure 7-1 presents total PFC emissions from aluminum production under the technology-adoption baseline scenario from 1990 through 2020. Between 1990 and 1995, global emissions declined from 98 to 61 MtCO_2eq . This significant decline was the result of voluntary measures undertaken by global smelters to reduce their AE minutes per cell day. These measures included incremental improvements in smelter technologies and practices, and a shift in the share of SWPB-related production to more state-of-the-art PFPB facilities. Although a continuation of this AE minute reduction trend occurred through 2000, emissions reductions were offset by a 24 percent increase in global aluminum production between 1995 and 2000.

The declining global emissions levels through 2010 reflect the successful adoption of IAI emissions reduction goals through both retrofits and a continued shift of production from VSS, HSS, and SWPB to PFPB. From 2010 through 2020, the emissions intensity is assumed to remain constant; consequently, emissions will be driven by increasing aluminum production. PFC emissions in OECD, as well as non-EU Eastern Europe, non-EU FSU, China/CPA, and S&E Asia are projected to remain relatively constant from 2010 through 2020, due to slowing aluminum production growth. Trends in the United States and the EU-25 reflect overall trends in the developed (OECD) countries. Africa, Latin America, and the Middle East are projected to increase their share of global emissions from 2010 through 2020, due to strong

Table 7-1: Total PFC Emissions from Aluminum Manufacturing (MtCO₂eq)—No-Action Baseline

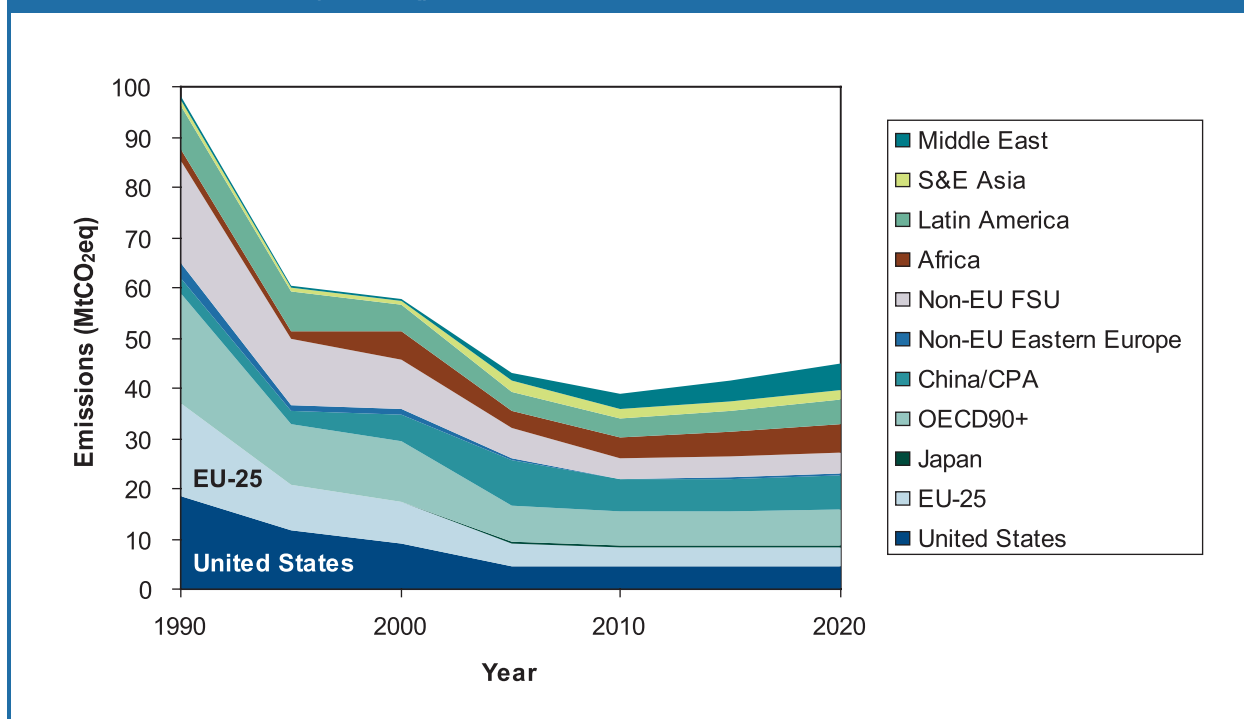
Country/Region	2000	2010	2020
Africa	5.6	6.0	8.6
Annex I	37.3	37.8	38.3
Australia/New Zealand	3.5	2.8	2.8
Brazil	3.9	3.5	4.7
China	5.2	13.2	13.5
Eastern Europe	2.9	1.2	1.2
EU-15	8.1	4.7	4.7
India	0.8	2.2	2.4
Japan	0.0	0.2	0.2
Mexico	0.1	0.1	0.1
Non-OECD Annex I	9.2	8.3	8.2
OECD	28.1	29.6	30.2
Russian Federation	7.5	7.4	7.3
South & SE Asia	0.2	0.8	0.8
United States	9.0	14.7	14.7
World Total	57.8	69.8	77.1

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Table 7-2: Total PFC Emissions from Aluminum Manufacturing (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2000	2010	2020
Africa	5.6	4.0	5.7
Annex I	37.4	18.9	19.6
Australia/New Zealand	3.5	2.5	2.5
Brazil	3.9	2.4	3.2
China	5.2	6.5	6.7
Eastern Europe	2.9	0.8	0.8
EU-15	8.1	3.5	3.5
India	0.8	1.2	1.3
Japan	0.0	0.1	0.1
Mexico	0.1	0.1	0.1
Non-OECD Annex I	9.3	3.9	3.9
OECD	28.2	15.0	15.8
Russian Federation	7.5	3.3	3.3
South & SE Asia	0.2	0.6	0.7
United States	9.0	4.6	4.4
World Total	58.0	39.1	44.7

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Figure 7-1: PFC Emissions from Aluminum Production Based on a Technology-Adoption Scenario—1990–2020 (MtCO₂eq)

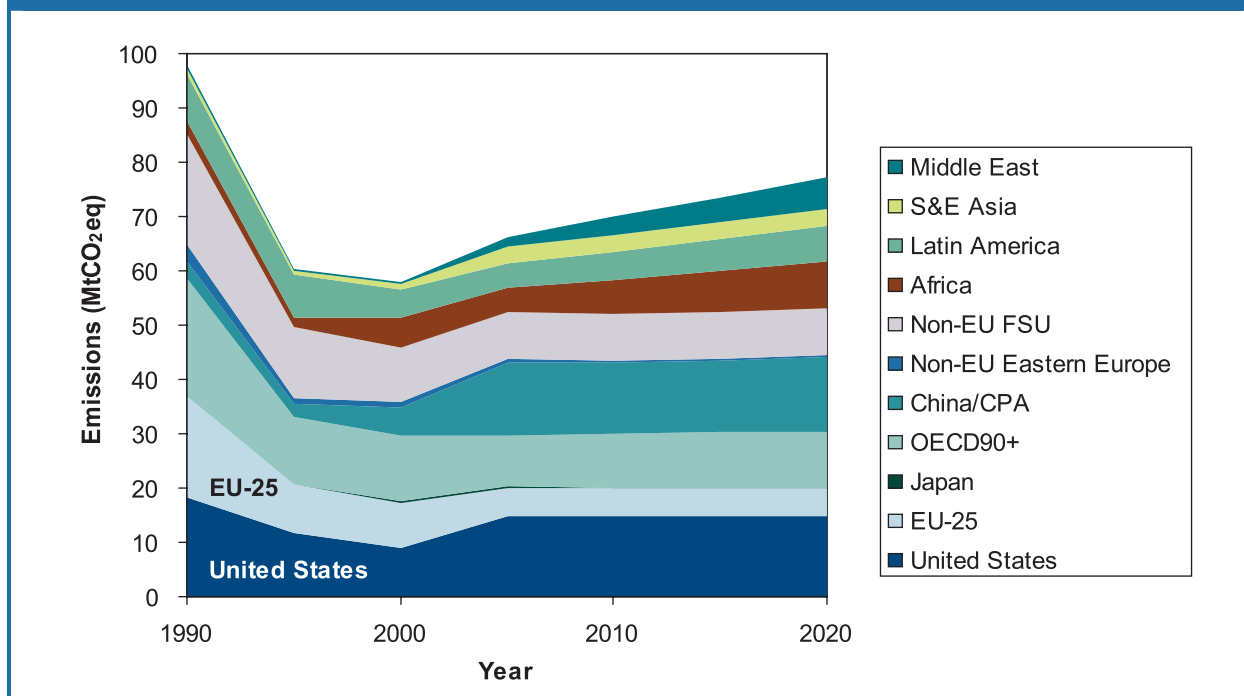
CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation of Economic Co-operation and Development; S&E Asia = Southeast Asia.

growth in aluminum production. In 2020, China/CPA, Latin America, Africa, and the Middle East are expected to collectively account for 50 percent of global emissions. In comparison, OECD is projected to account for 36 percent of global emissions, down from 51 percent in 2000.

IV.7.2 No-Action Baseline

Under the no-action baseline scenario, it is assumed that aluminum producers will take no retrofit actions to reduce their emissions below the levels of the late 1990s; as a result, emissions projections do not reflect anticipated technology adoptions and/or the implementation of improved work and management practices to reduce emissions. Figure 7-2 presents total PFC emissions from aluminum production under the no-action baseline scenario from 1990 through 2020. The trends from 1990 through 2000 are the same as those in the technology-adoption baseline. From 2000 through 2020, no additional abatement retrofits are assumed to occur; however, as in the technology-adoption baseline, it is assumed that the global historical trend in the shift of production from SWPB to PFPB continues (IAI, 2000, 2005b). Based on these assumptions, global emissions under this scenario rise to 77 MtCO₂eq in 2020, a 33 percent increase over 2000 levels. This is primarily driven by increasing global aluminum production.

In 1990, OECD emissions accounted for approximately 60 percent of global emissions; however, by 2020, this share is reduced to 40 percent in this scenario. This reduction is the result of relatively flat aluminum production levels between 2000 and 2020, as cheaper aluminum from developing countries enters the global marketplace. The primary sources of this cheaper aluminum are China/CPA, the Middle East, Latin America, and Africa, which in 2020 are projected to have production levels approximately

Figure 7-2: PFC Emissions from Aluminum Production Based on a No-Action Scenario—1990–2020 (MtCO₂eq)

CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation of Economic Co-operation and Development; S&E Asia = Southeast Asia.

200 percent greater than their 2000 levels. In 2020, China/CPA is projected to account for 17.5 percent of global emissions, compared with 3 percent in 1990 and 9 percent in 2000.

The EU-25 and the United States reflect the general OECD trend, except that between 2000 and 2005 there is an increase in U.S. emissions and a decrease in EU emissions. The decrease in EU emissions is primarily the result of their transition from SWPB to PFPB technology. The increase in U.S. emissions is an artifact of the baseline calculation methodology. Past U.S. emissions reflect reductions already implemented by members of the USEPA's Voluntary Aluminum Industrial Partnership, but under this scenario, future U.S. emissions (from 2005 forward) are projected to occur at a higher rate.

IV.7.3 Cost of PFC Emissions Reduction from Aluminum Production

IV.7.3.1 Abatement Options

The most direct and cost-efficient method to reduce PFC emissions and improve process efficiency is to retrofit existing aluminum production technology. Two types of retrofit options can be implemented: (1) installation or refinement of process computer control systems, and (2) the installation or conversion to alumina point-feed systems. The installation of process computer controls can be considered a minor retrofit, whereas the installation of alumina point-feed systems can be considered a major retrofit. These two reduction technologies are not mutually exclusive, but additive. In fact, point-feed systems require computer controls in order to be effective, although the reverse is not true.

In this analysis, these two options are assumed to be adopted in succession. At relatively low carbon prices, computer controls are adopted by 100 percent of the market (i.e., 100 percent of a given cell technology) and at higher carbon prices, alumina point feed systems are adopted by 100 percent of the

market. The costs and reductions of installing alumina point-feed systems are additive to those of installing computer controls. (Of course, if carbon prices are high enough at the outset, the two options will not be adopted successively in time, but simultaneously. In any event, the MACs provide an accurate measure of the potential reductions at all carbon prices.)

Cost and Reduction Assumptions

Cost assumptions for each mitigation option are based on information reported in *Greenhouse Gas Emissions from the Aluminum Industry* (IEA, 2000). The remainder of Section IV.7.2.1 will provide an overview of each abatement option and detail the cost assumptions used.

Table 7-3 provides a summary of the potential reduction opportunities associated with each mitigation option. The reduction efficiencies of complete retrofits (i.e., retrofits including installation of both computer controls and point-feed systems) were estimated by assuming that after implementation of the complete retrofit, the cell will operate (and emit PFCs) as a PFPB cell. Consequently, the reduction efficiencies were based on the differences between the PFC emissions rates (tCO₂eq/t Al) of unabated VSS, HSS, SWPB, and CWPB cells and the PFC emissions rate of PFPB cells. The emissions rates of unabated VSS, HSS, SWPB, and CWPB cells were represented by the average global 1995 emissions rates of those technologies, because the market penetration of minor and major retrofits was believed to be small in 1995. The complete retrofit reduction efficiencies range from 41 to 93 percent, depending on cell type.

Table 7-3: Reduction Efficiency Potential for Abatement Option by Cell Type (Percent)

Abatement Option	Cell Technology Type			
	VSS	HSS	SWPB	CWPB
Computer controls (minor retrofit)	35.5%	33.5%	23%	31%
Point-feed (major retrofit)	35.5%	33.5%	70%	10%
Complete retrofit (both)	71.0%	77.0%	93%	41%

The distribution of maximum reduction efficiencies (i.e., those associated with complete retrofits) between minor and major retrofits was estimated based on communications with industry (Marks, 2006). For VSS and HSS, it was assumed that reductions are evenly split (i.e., minor and major retrofits each achieve 50 percent of the reductions of a complete retrofit). For SWPB, 25 percent of the total reduction was assumed to result through implementation of the minor retrofit, with the remainder occurring through the major retrofit. For CWPB, 75 percent of the total reduction was assumed to occur through implementation of the minor retrofit, whereas 25 percent was assumed to occur through implementation of the major retrofit.

Although PFPB systems can be further improved through the implementation of control software (Marks, 2006), this analysis assumes that retrofit abatement options will occur only on existing VSS, HSS, SWPB, and CWPB technologies.

Because the PFC abatement options are based on the retrofitting of existing cell technologies and not on a major change in technology, the maximum market penetration available is assumed to be 100 percent of emissions from the VSS, HSS, SWPB, and CWPB cell type production lines. However, the applicability of cell type-specific retrofit options to baseline emissions is dependent on the country-level distribution of cell technologies.

Installation/Refinement of Computer Controls (Minor Retrofit)

The minor retrofit option includes the installation of process computer control systems or the refinement of existing process control algorithms. Computer systems provide greater control over alumina feeding, enable control of the repositioning of the anodes as they are consumed during aluminum production, and enhance the ability to predict and suppress AEs. Consequently, computer systems have the potential to increase productivity, lower energy costs, and reduce PFC emissions. The minor retrofit option is assumed to have the potential to reduce PFC emissions factors (tCO₂eq/t Al) by between 23 percent and 36 percent, depending on the cell type (see Table 7-4).

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** For a typical facility that produces 200,000 tonnes of aluminum, capital costs are assumed to range from \$4.2 to \$5.1 million, depending on the cell type (IEA, 2000).
- **Annual Costs.** Implementation of the minor retrofit option is assumed to produce an incremental increase in operating costs between 2 and 3 percent per year depending on the cell technology type. Operating costs are assumed to include costs associated with operation and maintenance labor and with overhead and administrative costs. Country-specific operating costs are determined by applying the incremental operating cost associated with this option to the regional baseline operating costs developed for IEA (2000).
- **Cost Savings.** The reduction in AE minutes per cell day produced by the mitigation option is assumed to result in a corresponding increase in aluminum production. This analysis assumes that the cost of aluminum is \$1,400 per metric ton. Additional cost savings from reduced aluminum fluoride losses and energy consumption were estimated using assumptions detailed in *Estimating the Cost of an Anode Effect* (USEPA, 2002).

Installation of Point-Feed Systems (Major Retrofit)

The major retrofit option includes only the installation of alumina point-feed systems. This option is considered to take place in addition to the implementation of the minor retrofit. The benefits and costs associated with the minor retrofit option are considered fully implemented and therefore are not included in the analysis of this option. The implementation of this option results in improved cell performance and increased PFC emissions reductions.

The alumina point-feed system allows alumina to be fed at shorter time intervals and at different positions along the bath, compared with feeding techniques used by existing VSS, HSS, SWPB, and CWPB cells. PFC emissions occur as alumina levels in the cell bath decline, typically below 2 percent by weight of cell bath composition (Dugois, 1994), and the remaining fluorine-containing bath components begin to undergo electrolysis. Since AEs can be terminated through the addition of more alumina, point feeding will ensure that alumina is fed continuously into the central parts of the cell, where the bath area is largest. Furthermore, point feeding also increases the cell current efficiency and consequently reduces the cell electricity consumption. The major retrofit option is assumed to have the potential to reduce PFC emissions factors by between 10 and 70 percent, depending on the technology type (see Table 7-4).

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** Capital costs for VSS and HSS cells are assumed to be approximately \$39 million (IEA, 2000), whereas those for SWPB cells are assumed to be approximately \$82 million (Marks, 2006). For CWPB cells, capital costs are approximately \$3.5 million (IEA, 2000).
- **Annual Costs.** Implementation of the major retrofit option is assumed to produce an incremental increase in operating costs between 1 and 3 percent per year, depending on the cell technology

type. Operating costs are assumed to include costs associated with operation and maintenance labor and with overhead and administrative costs (IEA, 2000).

- **Cost Savings.** Similar to the minor retrofit option, cost savings include benefits associated with avoided aluminum production losses, reduced electricity consumption, and reduced aluminum fluoride losses. For this analysis, it is assumed that the cost of aluminum is \$1,400 per metric ton. Assumptions used to estimate benefits associated with reduced energy consumption and fluoride losses are detailed in *Estimating the Cost of an Anode Effect* (USEPA, 2002).

Industry experts indicate that if the computer control system is installed separately from the point-feed system, particularly if it is installed several years earlier, the computer control system is likely to require an update in its software to accommodate the point-feed system. The costs of such an update are not included in this analysis. However, the USEPA believes that these costs are likely to be small relative to the costs of the point-feed system itself.

Baseline Market Penetration of Options in No-Action and Technology-Adoption Baselines

The reductions achieved by each technology in each scenario are based not only on the reduction efficiency and maximum market penetration of that technology but also on the share of the market that is already claimed by the technology in the baseline of concern. For example, if a technology had already achieved a 100 percent market penetration in the baseline of concern, no reductions from that technology would be available in the MAC associated with that baseline.

In both the no-action and technology-adoption scenarios, there is some baseline market penetration by the minor and major retrofit options. In the no-action scenario, plant operators outside of the United States are assumed to have adopted complete retrofits to the extent required to achieve the 2000 emissions factor for each technology, which is significantly lower than the 1995 emissions factor.¹ In the technology-adoption scenario, plant operators are assumed to have adopted complete retrofits to the extent required to achieve the 2010 IAI goal of reducing emissions intensities by 80 percent relative to the 1990 level. Table 7-4 shows the global average baseline market penetrations of complete retrofits in both scenarios.

Table 7-4: Average^a Baseline Market Penetration of Complete Retrofits by Cell Type and Scenario (Percent)

Scenario	Cell Technology Type			
	VSS	HSS	SWPB	CWPB
No-action	30%	21%	16%	52%
Technology-adoption	98%	75%	24%	94%

^a These are global averages. Individual countries may have slightly larger or slightly smaller baseline market penetrations.

For the United States, the baseline market penetration of retrofits in the no-action scenario is assumed to be zero. This is because the U.S. no-action baseline emissions are based on a 1990 emissions factor, and few if any retrofits are believed to have been performed by 1990.

The assumption that complete retrofits were adopted in all cases is a simplification; in fact, it is likely that some plant operators have adopted only minor retrofits. If this were explicitly modeled in the analysis, the baseline market penetration of minor retrofits would grow, while that of major retrofits

¹ Although the various types of cells (VSS, SWPB, etc.) become PFPB cells after implementation of a complete retrofit, the IEA model, which was used as the basis for this analysis, continues to track converted cells under their old cell technologies. Thus, it is reasonable to treat retrofits this way in this context.

would decline. Thus, this analysis may overestimate the reductions available from minor retrofits and underestimate those available from major retrofits.

IV.7.4 Results

This section discusses the results from the MAC analysis for the world and for various regions for the no-action and technology-adoption scenarios.

IV.7.4.1 Data Tables and Graphs

Tables 7-5 through 7-10 provide a summary of the potential emissions reduction opportunities and associated costs for various regions in 2010 and 2020 under the no-action and technology-adoption scenarios. The costs to reduce 1 tCO₂eq are presented at a 10 percent discount rate and 40 percent tax rate.

Table 7-5: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.17	2.56	3.23	3.23	3.23	3.23
Annex I	3.88	12.28	17.45	17.45	17.45	17.45
Australia/New Zealand	0.31	0.44	0.44	0.44	0.44	0.44
Brazil	0.29	1.49	1.91	1.91	1.91	1.91
China	2.84	3.48	6.78	6.78	6.78	6.78
Eastern Europe	0.22	0.48	0.62	0.62	0.62	0.62
EU-15	0.00	1.60	1.90	1.90	1.90	1.90
India	0.45	0.65	1.13	1.13	1.13	1.13
Japan	0.00	0.05	0.11	0.11	0.11	0.11
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	1.91	2.79	5.22	5.22	5.22	5.22
OECD	1.97	9.49	12.23	12.23	12.23	12.23
Russian Federation	1.83	2.42	4.68	4.68	4.68	4.68
South & SE Asia	0.14	0.18	0.18	0.18	0.18	0.18
United States	1.14	6.18	7.48	7.48	7.48	7.48
World Total	9.50	21.77	31.90	31.90	31.90	31.90

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Table 7-6: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.72	3.64	4.65	4.65	4.65	4.65
Annex I	3.87	12.47	17.80	17.80	17.80	17.80
Australia/New Zealand	0.31	0.44	0.44	0.44	0.44	0.44
Brazil	0.36	1.97	2.62	2.62	2.62	2.62
China	2.74	3.60	6.99	6.99	6.99	6.99
Eastern Europe	0.22	0.48	0.61	0.61	0.61	0.61
EU-15	0.00	1.62	1.94	1.94	1.94	1.94
India	0.45	0.70	1.22	1.22	1.22	1.22
Japan	0.00	0.07	0.15	0.15	0.15	0.15
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	1.85	2.77	5.17	5.17	5.17	5.17
OECD	2.02	9.70	12.63	12.63	12.63	12.63
Russian Federation	1.77	2.38	4.61	4.61	4.61	4.61
South & SE Asia	0.15	0.19	0.19	0.19	0.19	0.19
United States	1.14	6.18	7.48	7.48	7.48	7.48
World Total	10.16	23.86	34.86	34.86	34.86	34.86

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Table 7-7: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.35	1.40	1.40	1.40	1.40	1.40
Annex I	0.40	2.40	2.93	2.93	2.93	2.93
Australia/New Zealand	0.06	0.15	0.15	0.15	0.15	0.15
Brazil	0.19	0.81	0.86	0.86	0.86	0.86
China	0.02	0.22	0.41	0.41	0.41	0.41
Eastern Europe	0.07	0.27	0.28	0.28	0.28	0.28
EU-15	0.00	0.87	0.87	0.87	0.87	0.87
India	0.01	0.07	0.12	0.12	0.12	0.12
Japan	0.00	0.02	0.04	0.04	0.04	0.04
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.16	0.56	0.85	0.85	0.85	0.85
OECD	0.24	1.84	2.08	2.08	2.08	2.08
Russian Federation	0.12	0.36	0.60	0.60	0.60	0.60
South & SE Asia	0.02	0.02	0.02	0.02	0.02	0.02
United States	0.18	0.64	0.81	0.81	0.81	0.81
World Total	1.14	5.31	6.13	6.13	6.13	6.13

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Table 7-8: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Aluminum Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.49	1.95	1.95	1.95	1.95	1.95
Annex I	0.40	2.47	3.06	3.06	3.06	3.06
Australia/New Zealand	0.06	0.15	0.15	0.15	0.15	0.15
Brazil	0.24	1.03	1.10	1.10	1.10	1.10
China	0.02	0.28	0.54	0.54	0.54	0.54
Eastern Europe	0.07	0.27	0.27	0.27	0.27	0.27
EU-15	0.00	0.87	0.87	0.87	0.87	0.87
India	0.02	0.09	0.15	0.15	0.15	0.15
Japan	0.00	0.02	0.05	0.05	0.05	0.05
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.15	0.57	0.87	0.87	0.87	0.87
OECD	0.24	1.90	2.20	2.20	2.20	2.20
Russian Federation	0.11	0.37	0.61	0.61	0.61	0.61
South & SE Asia	0.02	0.02	0.02	0.02	0.02	0.02
United States	0.18	0.65	0.81	0.81	0.81	0.81
World Total	1.34	6.24	7.24	7.24	7.24	7.24

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Table 7-9: Emissions Reduction and Costs in 2020—No-Action Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Computer controls: SWPB	−\$2.44	\$0.73	1.85	2.4%	1.85	2.4%
Computer controls: VSS	−\$5.75	\$0.75	8.25	10.7%	10.11	13.1%
Computer controls: HSS	\$0.71	\$4.75	2.74	3.6%	12.85	16.7%
Computer controls: CWPB	−\$16.93	\$6.13	4.09	5.3%	16.94	22.0%
Point feed: SWPB	\$6.27	\$6.98	5.56	7.2%	22.50	29.2%
Point feed: CWPB	−\$9.35	\$14.17	1.36	1.8%	23.86	31.0%
Point feed: HSS	\$19.21	\$23.25	2.74	3.6%	26.61	34.5%
Point feed: VSS	\$20.37	\$26.88	8.25	10.7%	34.86	45.2%

Table 7-10: Emissions Reduction and Costs in 2020—Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Computer controls: SWPB	−\$2.44	\$0.73	1.22	2.7%	1.22	2.7%
Computer controls: VSS	−\$5.75	\$0.75	0.20	0.5%	1.43	3.2%
Computer controls: HSS	\$0.71	\$4.75	0.80	1.8%	2.23	5.0%
Computer controls: CWPB	−\$16.93	\$6.13	0.26	0.6%	2.48	5.5%
Point feed: SWPB	\$6.27	\$6.98	3.67	8.2%	6.16	13.8%
Point feed: CWPB	−\$9.35	\$14.17	0.09	0.2%	6.24	14.0%
Point feed: HSS	\$19.21	\$23.25	0.80	1.8%	7.04	15.7%
Point feed: VSS	\$20.37	\$26.88	0.20	0.5%	7.24	16.2%

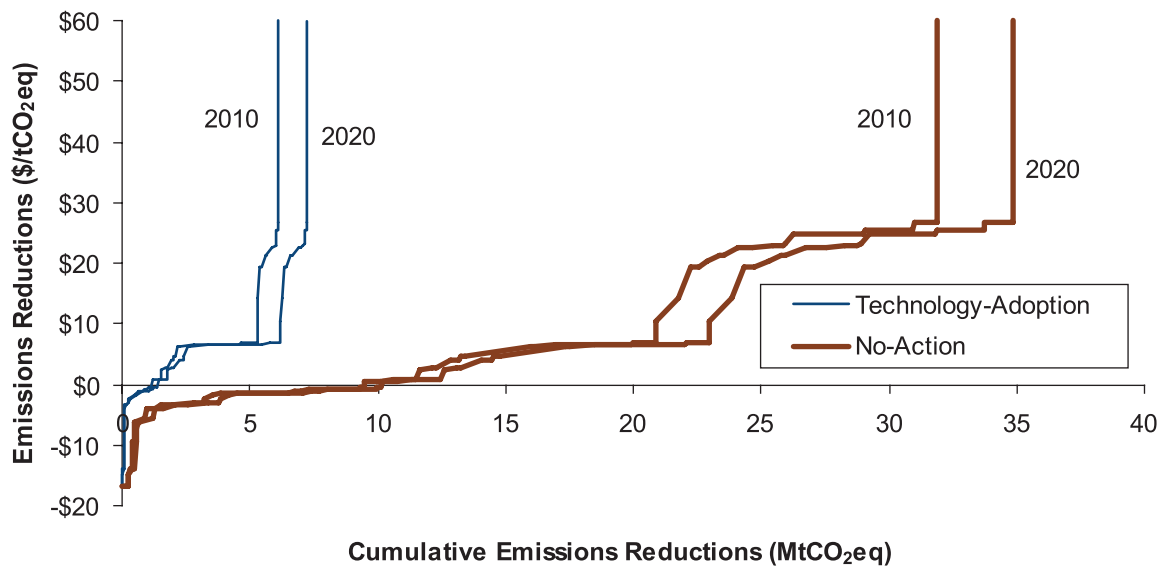
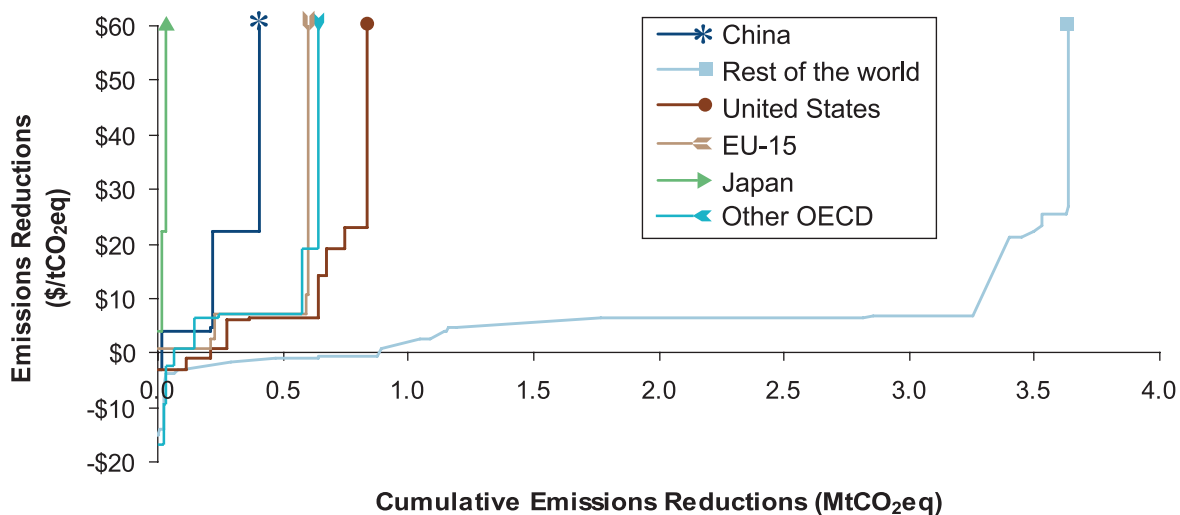
IV.7.4.2 Global and Regional MACs and Analysis

This section discusses the results from the MAC analysis for the world and by region, including China, Japan, the United States, the EU-15, other OECD, and the rest of the world.

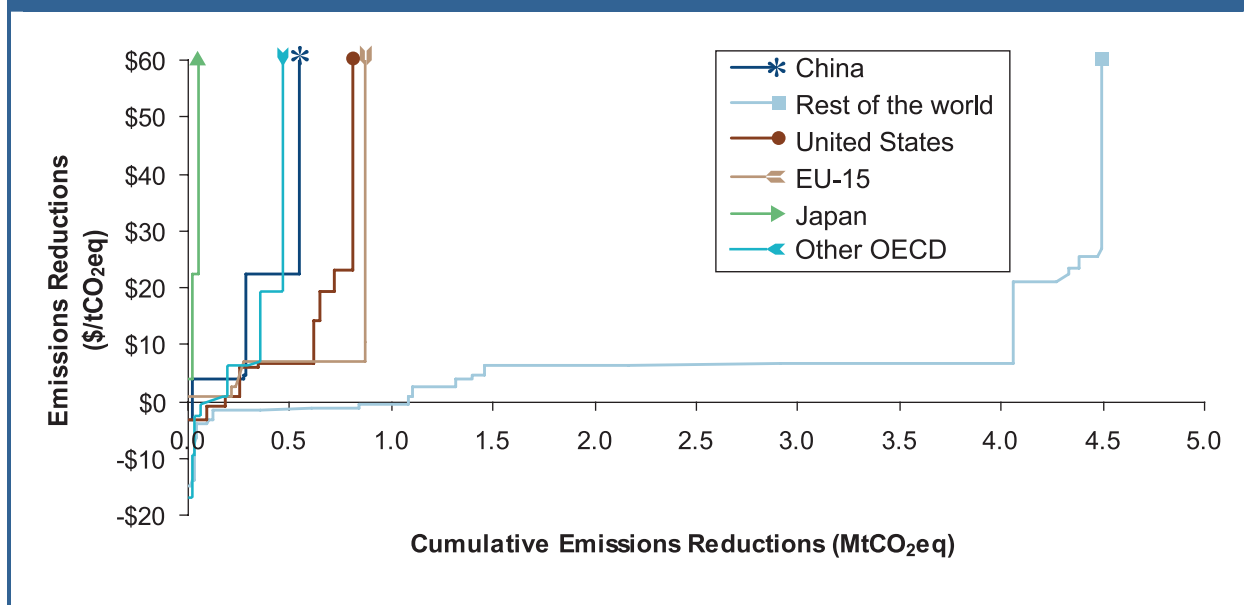
Figure 7-3 presents the 2010 and 2020 global technology-adoption and no-action MACs for aluminum production. The difference in abatable emissions between the technology-adoption and no-action MACs reflects the impact of retrofits adopted globally to meet IAI's PFC emissions reduction goal. The technology-adoption baseline reflects the IAI goal, which is to reduce the global PFC emissions intensity to 80 percent below 1990 levels by 2010. In contrast, the no-action baseline and MACs assume that aluminum producers will implement no retrofit actions beyond those necessary to achieve year 2000 emissions rates.

For the technology-adoption and no-action global MACs, operational and capital costs for implementing retrofits, as well as the global PFC emissions intensities for smelter technologies, are assumed to remain constant between 2010 and 2020. Consequently, for both MAC scenarios, changing aluminum production levels represents the primary driver for MAC curve shifts between 2010 and 2020. Most of this increased production is expected to occur in the other OECD and rest of the world regions (specifically in Africa and Latin America). The shift to the right is greater in the no-action global MACs because of the larger presence of non-retrofitted smelters in all global regions. That is, while the technology-adoption MACs assume that all CWPB, SWPB, as well as a majority of VSS and HSS smelters, have been retrofitted to PFPB, the no-action MACs assume that no changes have occurred since 2000.

Figures 7-4 and 7-5 present 2010 and 2020 regional technology-adoption MACs for China, Japan, the United States, the EU-15, other OECD, and the rest of the world. The 2020 regional MACs reflect the successful and continuing attainment of IAI's 2010 global PFC emissions intensity goal, which is expected to be achieved by retrofitting Soderberg and SWPB smelters with computer control systems and point-feeding systems. As a result, relatively limited emissions reductions are available in Japan, the United States, China, the EU-15, and other OECD countries in 2010. Where reductions are available, they will predominantly occur at those smelters that still utilize HSS and SWPB-based technologies. SWPB retrofits to PFPB will generally occur before HSS. SWPB retrofit costs range between −\$2.4 and \$7/tCO₂eq, compared with \$0.7 to \$23/tCO₂eq for HSS. In 2010, most VSS smelters are assumed to have undergone

Figure 7-3: 2010 and 2020 Global Technology-Adoption and No-Action MACs for Primary Aluminum Production**Figure 7-4: 2010 Regional Technology-Adoption MACs for Primary Aluminum Production**

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

Figure 7-5: 2020 Regional Technology-Adoption MACs for Primary Aluminum Production

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development

retrofit through voluntary actions, and therefore only limited reductions are still available for this cell type. For the remaining rest of the world countries, significant reductions in the MAC will occur in Africa, Brazil, and the Russian Federation (i.e., these regions account for over 80 percent, approximately 3 MtCO₂eq, of the rest of the world reductions). For both Africa and Brazil, significant SWPB-based production is expected to continue to occur, and thus be available for retrofit to PFPB. In the Russian Federation, VSS, HSS, and SWPB-based production is assumed to continue to occur.

As in 2010, the majority of emissions reductions in 2020 are expected to be available in the rest of the world, specifically Africa, Brazil, and the Russian Federation (Figure 7-5). Again reductions are expected to occur predominantly through the retrofit of HSS and SWPB smelters. On a global basis, approximately 70 percent of reductions will occur at SWPB smelters. Because SWPB retrofits are relatively inexpensive, this means that most of the reductions (6.2 MtCO₂eq) will be available for less than \$7/tCO₂eq. Another 0.9 MtCO₂eq will be available between \$7 and \$24/tCO₂eq, primarily from the major retrofit of HSS smelters. (Major and minor HSS smelter retrofits account for approximately 22 percent of global emissions reductions.) The majority of HSS retrofits are expected to occur in China and the Russian Federation.

IV.7.4.3 Uncertainties and Limitations

Uncertainties and limitations persist despite attempts to incorporate all publicly available information on international aluminum production. Some key areas of uncertainty within the aluminum MAC modeling methodology are provided below.

Aluminum Production

A major source of uncertainty in the MACs is due to variation in aluminum production for all countries. Aluminum production is highly variable, with operations coming on- and offline as market forces fluctuate; thus, a simple measure of capacity is not always indicative of actual production, especially for long-range projections. Also, production fluctuations between cell types within a given country can significantly affect the emissions estimates, because different cell types have significantly

different emissions rates. The USEPA modeled documented Soderberg and SWPB to PFPB technology shifts (IAI, 2005a) in the no-action and technology-adoption baselines; however, recent environmental factors, as well as increasing energy costs, have resulted in the shutdown of many Soderberg smelters (Marks, 2006). Consequently, technology mix assumptions used in this analysis may not represent actual technology mix conditions in global aluminum markets.

Baseline Market Penetration of Retrofits

The USEPA has modeled the baseline market penetration of retrofits in both the no-action and technology-adoption scenarios on a cell-type- and country-specific basis. However, the information used in the model (from IEA, 2000) is now several years old, and it may not reflect the actual adoption of retrofits globally. Thus, the reductions available for the various cell types may be over or underestimated.

Cost Savings

Benefits associated with reduced energy consumption and fluoride losses were calculated using assumptions detailed in *Estimating the Cost of an Anode Effect* (USEPA, 2002). However, this cost savings is dependent on a number of factors, such as the type of power system installed at smelters (e.g., constant power consumption systems, which are used by most aluminum smelting facilities; or constant potline current or amperage systems), which can vary significantly depending on smelter technology-types, age, and operational characteristics. Consequently, conservative assumptions were applied when estimating potential cost savings. Generally, these savings were estimated to be on the order of 1 to 4 percent of total realized cost savings, of which the primary contributor is avoided aluminum production losses.

Adjusting Costs for Specific Domestic Situations

Currently, the technologies considered in this report are widely available. However, individual countries may be faced with higher costs from transportation and tariffs associated with purchasing the technology from abroad or with lower costs from domestic production of these technologies. Data on domestically produced and implemented retrofit technologies in individual countries are not available.

Emissions Reduction Effectiveness of Retrofit Technologies

The PFC emissions factor reductions used for the minor and major retrofits may vary significantly depending on various operational conditions (e.g., cell conditions, plant operator effectiveness). Additionally, as technologies and control software evolve, additional reduction opportunities are likely to occur. For example, recently Alcan Pechiney reported improved software and feed systems that have the potential to make substantial reductions in emissions on cells that are already considered to be high performing relative to PFC emissions (Marks, 2006). Any deviation from the assumed emissions reduction potential of the retrofits would have a direct impact on estimated emissions.

IV.7.5 References

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IV.8 HFC-23 Emissions from HCFC-22 Production

IV.8.1 Source Description

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

Nearly all producers in developed countries have implemented process optimization or thermal destruction to reduce HFC-23 emissions. In a few cases, HFC-23 is collected and used as a substitute for ODSs, mainly in very-low temperature refrigeration and air-conditioning systems. Emissions from this use are quantified in the Air Conditioning and Refrigeration chapters and are therefore not included here. HFC-23 exhibits the highest GWP of the HFCs—11,700 under a 100-year time horizon—with an atmospheric lifetime of 264 years. Baseline emissions estimates under both a technology-adoption and a no-action baseline scenario are presented in Tables 8-1 and 8-2.

Table 8-1: Total HFC-23 Emissions from HCFC-22 Production (MtCO₂eq)—No-Action Baseline

Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	51.0	29.6	26.3
Australia/New Zealand	0.0	0.0	0.0
Brazil	0.1	0.2	0.2
China	33.3	70.2	91.0
Eastern Europe	0.0	0.0	0.0
EU-15	6.5	1.8	1.0
India	4.7	8.0	9.2
Japan	13.6	0.8	0.9
Mexico	2.6	4.0	4.3
Non-OECD Annex I	1.1	0.7	0.3
OECD	56.2	38.6	36.6
Russian Federation	1.1	0.7	0.3
South & SE Asia	0.0	0.0	0.0
United States	29.8	26.3	24.0
World Total	95.6	118.0	137.5

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 8-2: Total HFC-23 Emissions from HCFC-22 Production (MtCO₂eq)—Technology-Adoption Baseline

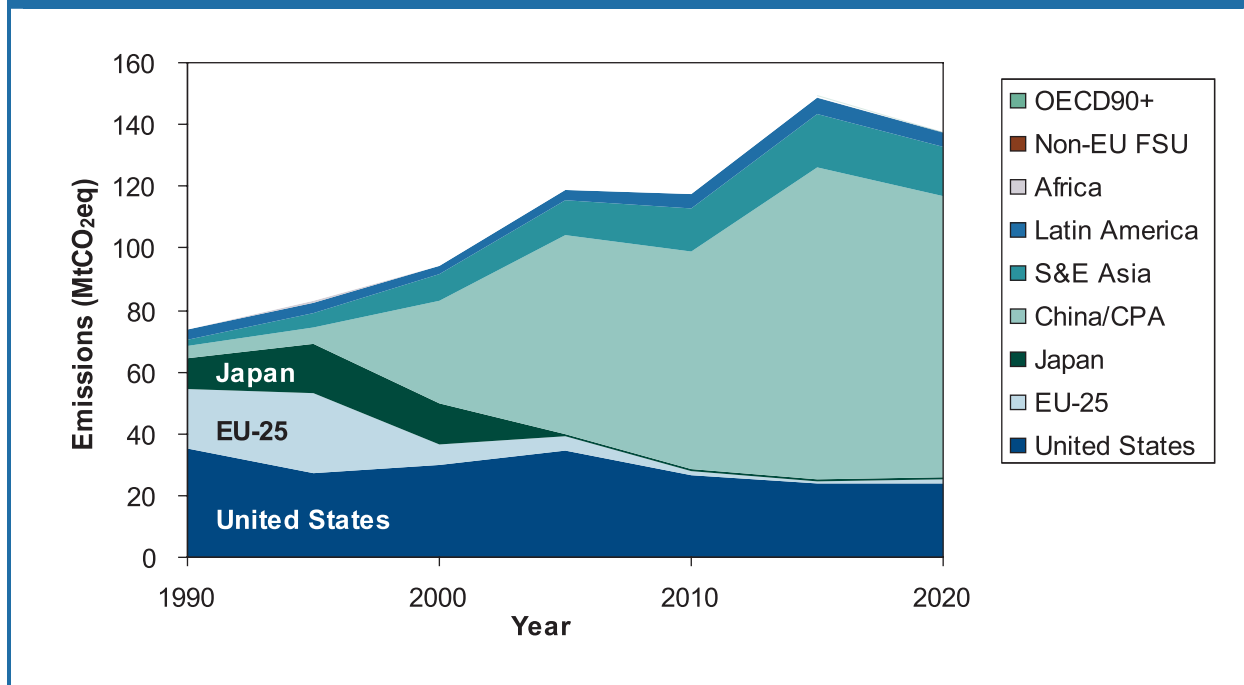
Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	51.0	11.4	10.1
Australia/New Zealand	0.0	0.0	0.0
Brazil	0.1	0.2	0.2
China	33.3	27.0	47.8
Eastern Europe	0.0	0.0	0.0
EU-15	6.5	0.6	0.4
India	4.7	1.1	2.3
Japan	13.6	0.8	0.9
Mexico	2.6	0.3	0.6
Non-OECD Annex I	1.1	0.7	0.3
OECD	56.2	15.4	15.3
Russian Federation	1.1	0.7	0.3
South & SE Asia	0.0	0.0	0.0
United States	29.8	9.3	8.5
World Total	95.6	44.7	66.2

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.8.1.2 No-Action Baseline

Under the no-action baseline scenario, it is assumed that HCFC-22 producers will take no further action to reduce their emissions; as a result, emissions projections do not reflect anticipated technology adoptions to reduce emissions. Under this scenario, world HFC-23 emissions from HCFC-22 production are expected to grow by an additional 56 percent between 2000 and 2015, but emissions are expected to decline between 2015 and 2020 as a result of the phaseout of nonfeedstock HCFC-22 production in developing countries.

Figure 8-1 reveals a striking shift: the majority of emissions will come from China and other developing countries rather than from the OECD countries. This is due to (1) a combination of increased use of emissions controls and the phaseout of HCFC-22 under the Montreal Protocol in OECD countries and (2) increased HCFC-22 production in China. (These drivers are discussed further below.) Thus, while HFC-23 emissions from developed countries are expected to decline by more than 60 percent from 1990 to 2020 in the no-action baseline, HFC-23 emissions in the China/CPA region are expected to increase dramatically. Southeast Asia and Latin America are also projected to show increasing emissions during this period. In 1990, the three largest emitters for this source were the United States, Japan, and France, which together accounted for more than two-thirds of all emissions. In 2020, the three largest emitters are projected to be China, India, and the United States. These nations are anticipated to account for 90 percent of all HFC-23 emissions, while China alone is expected to be the world's major HFC-23 emitter, accounting for more than 65 percent of total emissions.

Figure 8-1: HFC-23 Emissions from HCFC-22 Production Based on a No-Action Scenario—1990–2020 (MtCO₂eq)

CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = Organisation for Economic Co-operation and Development.

In the developed world, HFC-23 emissions decreased between 1990 and 2000 because of process optimization and thermal destruction, although there were increased emissions in the intervening years. The United States and EU drove these trends in the developed world. Although emissions increased in the EU-25 between 1990 and 1995 because of increased production of HCFC-22, a combination of process optimization and thermal oxidation led to a sharp decline in EU emissions after 1995, resulting in a net decrease in emissions of 67 percent for this region between 1990 and 2000. U.S. emissions also declined by 15 percent during the same period, despite a 35 percent increase in HCFC-22 production; however, during that time period, U.S. emissions demonstrated two distinct trends. Between 1990 and 1995, U.S. emissions declined by 23 percent because of a steady decline in the emissions rate of HFC-23 (i.e., the amount of HFC-23 emitted per kilogram of HCFC-22 manufactured). However, between 1995 and 2000, U.S. emissions increased because of increases in HCFC-22 production.¹

As illustrated in Figure 8-1 under the no-action baseline, HFC-23 emissions in developed countries are predicted to continue to decrease through 2020 as a result of (1) Japan's implementation of either thermal abatement or HFC-23 capture (for use) for 100 percent of its production beginning in 2005 (JICOP, 2006), (2) 100 percent implementation of thermal abatement in all EU countries except Spain by 2010, (3) closure of the HCFC-22 production plant in Greece in 2006, and (4) the HCFC-22 production phaseout scheduled under the Montreal Protocol.

¹ The apparent increase in U.S. emissions between 2000 and 2005 is an artifact of the method used to estimate U.S. emissions in the no-action baseline. Under this approach, the U.S. emissions factor was assumed to revert to its relatively high 1990 level in 2005, despite reductions in earlier years.

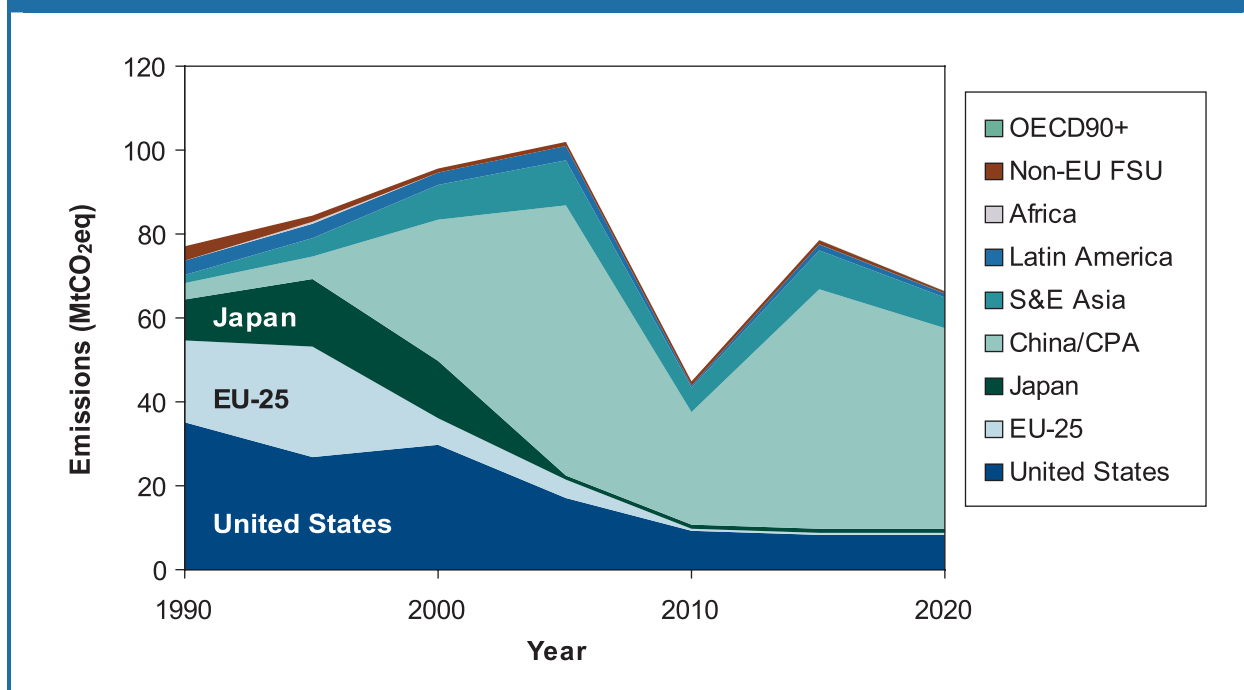
In the developing world, particularly China, emissions are increasing quickly because of a rapid increase in the production of HCFC-22. This production is meeting growing demand for unitary air-conditioning, commercial refrigeration, and substitutes for CFCs, which are currently being phased out in developing countries under the Montreal Protocol (UNEP, 2003). Under the no-action baseline, the increase in HFC-23 emissions is expected to continue through 2015, when HCFC-22 itself will begin to be phased out by developing countries for most end-uses under the Montreal Protocol.

IV.8.1.3 Technology-Adoption Baseline

Under the technology-adoption baseline scenario, it is assumed that HCFC-22 producers will introduce technologies and practices aimed at reducing HFC-23 emissions. Under this scenario, global HFC-23 emissions from HCFC-22 production are expected to decline by 35 percent between 2000 and 2020. These trends are mainly a result of the expected implementation of Clean Development Mechanism (CDM) projects in China, India, Korea, and Mexico, as well as implementation of thermal oxidation in Spain and the HCFC-22 production phaseout scheduled under the Montreal Protocol.

As seen in Figure 8-2, the most striking trend apparent in the technology-adoption baseline is the dramatic decline in emissions from China (and thus for the world, since by 2005 China accounts for the majority of emissions) between 2005 and 2010, followed by an increase in emissions from 2010 to 2015, at which point emissions again decline. The first dip in this zigzag pattern is caused by the implementation of CDM projects in China. Abatement is assumed to begin in 2010, decreasing emissions. However, while abatement (in absolute terms) is held constant through 2015 and 2020, emissions grow between 2010 and 2015 as a result of the increase in production of HCFC-22 in China (discussed in Section 8.1.2). The increase in HFC-23 emissions is then reversed after 2015, when HCFC-22 itself will begin to be phased out by developing countries for most end-uses.

Figure 8-2: HFC-23 Emissions from HCFC-22 Production Based on a Technology-Adoption Scenario—1990–2020 (MtCO₂eq)



CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = Organisation for Economic Co-operation and Development.

Emissions in OECD countries are expected to decline by 80 percent between 1995 and 2015. As Figure 8-2 shows, the majority of these emissions shift to China and other developing countries. This is due to (1) a combination of increased use of emissions controls and the phaseout of HCFC-22 in OECD countries and (2) increased HCFC-22 production in China. Thus, while HFC-23 emissions from developed countries are expected to decline by more than 80 percent from 1990 to 2020, HFC-23 emissions in the China/CPA region are expected to increase dramatically, despite the adoption of abatement measures under the CDM. Southeast Asia and Latin America are also projected to show increasing emissions through this period.

Global emissions in 1990 to 2000 follow the same trends as in the no-action baseline. As illustrated in Figure 8-2, HFC-23 emissions in developed countries as compared with the no-action baseline are predicted to decrease from 2010 through 2020, mainly as a result of the U.S. implementation of thermal abatement.

IV.8.2 Cost of HFC-23 Reduction from HCFC-22 Production

IV.8.2.1 Abatement Options

Historically, the majority of HFC-23 emissions have been vented to the atmosphere. However, two options have been identified as technically viable measures to reduce HFC-23 emissions from HCFC-22 production (IPCC, 2001):

- manufacturing process optimization and
- destruction of HFC-23 by thermal oxidation.

Process Optimization

Process optimization and modifications to production equipment can both optimize HCFC-22 production and reduce HFC-23 emissions. Process optimization is relatively inexpensive and is likely to be most effective in reducing the emissions from plants that are generating HFC-23 at a rate of 3 percent to 4 percent. Process optimization has been demonstrated to reduce emissions of fully optimized plants to below 2 percent of HCFC-22 production. This analysis assumes that all plants in developed countries have already implemented some optimization, resulting in HFC-23 emissions reductions. These plants may achieve further reductions through additional process optimization, but these reductions are likely to be more modest (Rand et al., 1999). Therefore, this option is not explicitly included as a mitigation option in this MAC analysis.

Thermal Oxidation

Thermal oxidation, the process of oxidizing HFC-23 to CO₂, HF, and water, is a demonstrated technology for the destruction of halogenated organic compounds. For example, destruction of more than 99 percent of HFC-23 can be achieved under optimal conditions (i.e., a relatively concentrated HFC-23 vent stream with a low flow rate) (Rand et al., 1999). In practice, actual reductions will be determined by the fraction of production time that the destruction device is actually operating. Units may experience some downtime because of the extreme corrosivity of HF and the high temperatures required for complete destruction. This analysis assumes a reduction efficiency of 95 percent.²

² A representative of a company that manufactures thermal oxidation systems stated that new systems are built using materials that better resist corrosion than the materials used in older systems. The representative indicated that such new systems were likely to experience very limited downtime, considerably less than 5 percent (Rost, 2006).

Although typical incinerators that burn only HFC-23 produce 6 pounds of CO₂ for every 1 pound of HFC-23 burned, almost all of the CO₂ produced is prevented from entering the atmosphere by scrubbers in the smoke stack. This reduction in CO₂ emissions occurs while scrubbing to remove HF from the waste stream (Oldach, 2000).

Cost and Reduction Assumptions

Cost estimates for thermal oxidation include the following assumptions:

- In the United States, total installed capital costs for a thermal oxidation system are assumed to be approximately \$3.4 million per plant in new plants (Rost, 2006) and \$4.4 million per plant in existing plants³ (Werling, 2006), with total annual operating costs of \$334,928 per year (Lehman, 2002). These capital and annual costs are assumed for the United States and the rest of the world, with the exception of the EU.
- In the EU, the total installed capital costs for a thermal oxidation system were estimated at \$2,834,447 million per plant, with total annual operating costs of \$188,963 per year (Harnisch et al., 2000).

Cost estimates for such systems are based upon the best available industry assessments; actual costs of some systems could differ from these estimates.

Reduction estimates for thermal oxidation include the following assumptions:

- Based on international HCFC-22 production capacity data from the Chemical Economics Handbook (CEH) (2001), the typical HCFC-22 plant outside of the EU was assumed to produce 20,000 tons of HCFC-22 annually. In the EU, plants were assumed to produce 10,000 tons of HCFC-22 annually (Harnisch et al., 2000).
- Plants were assumed to emit HFC-23 at a rate of 2 percent of HCFC-22 production.
- As noted above, thermal oxidation was assumed to destroy 95 percent of HFC-23 emissions at plants where it was applied.

Baseline Market Penetration of Thermal Oxidation

The maximum potential market penetration of this option is 100 percent. Thus, the abatement potential of the option for any given year and region depends on the difference between the baseline market penetration and 100 percent. Tables 8-3 and 8-4 present the baseline market penetration of thermal abatement for 2010 and 2020 for the no-action and technology-adoption baseline scenarios.

The no-action scenario accounts only for the level of implementation of thermal oxidation at the time this report was written. It does not account for additional implementation of thermal oxidation in the future. (For the United States, the no-action scenario actually assumes that current abatement ceases.) In contrast, the technology-adoption scenario accounts for additional implementation in the future. Most additional thermal oxidation is assumed to be installed in developing countries as they conduct mitigation projects, funded by developed countries under the CDM. The absolute level of abatement (in MtCO₂eq) for these projects is assumed to remain constant through 2020. Additional thermal oxidation is also modeled for Spain, where the owner of the sole HCFC-22 plant has announced plans to install thermal oxidation by 2010 (Campbell, 2006). These estimates are discussed in more detail in the USEPA report *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (2006).

³ Ralph Werling and Kurt Werner of 3M estimated that the costs of installing thermal oxidation systems in existing plants were 20 percent to 40 percent greater than the costs of installing the systems in new plants. This analysis assumes that it costs 30 percent more to install a thermal oxidation system in an existing plant than in a new plant.

Table 8-3: Baseline Market Penetration of Thermal Oxidation—No-Action Baseline

Country	2010	2020
France	100%	100%
Germany	100%	100%
Italy	100%	100%
Netherlands	100%	100%
Japan	100%	100%
Russian Federation	0%	0%
Spain	0%	0%
United Kingdom	100%	100%
United States	0%	0%
India	0%	0%
Brazil	0%	0%
Mexico	0%	0%
Venezuela	0%	0%
China	0%	0%
Korea, Republic of	0%	0%

Table 8-4: Baseline Market Penetration of Thermal Oxidation—Technology-Adoption Baseline

Country	2010	2020
France	100%	100%
Germany	100%	100%
Italy	100%	100%
Netherlands	100%	100%
Japan	100%	100%
Russian Federation	0%	0%
Spain	100%	100%
United Kingdom	100%	100%
United States	65%	65%
India	90%	78%
Brazil	0%	0%
Mexico	99%	91%
Venezuela	0%	0%
China	65%	50%
Korea, Republic of	26%	23%

Estimating Emissions from New Plants

The analysis also differentiates between emissions coming from new plants and those coming from existing plants as different costs are associated with the abatement of these two sets of emissions. To calculate emissions from new plants, it is assumed that all emissions growth after 2010 comes from new plants. Since only developing countries will experience emissions growth after 2010, all new plants are assumed to be built in developing countries.

IV.8.3 Results

This section discusses the result from the MAC analysis for the world and several regions for the no-action and technology-adoption scenarios.

IV.8.3.1 Data Tables and Graphs

Based on the trends described above, the USEPA developed MACs for the world and several regions. Tables 8-5 through 8-8 summarize the potential emissions reduction opportunities and associated costs for the world and several regions in 2010 and 2020 for the no-action and technology-adoption baselines. The costs to reduce 1 tCO₂eq are presented for a discount rate of 10 percent and a tax rate of 40 percent.

Table 8-5: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	26.80	26.80	26.80	26.80	26.80
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.19	0.19	0.19	0.19	0.19
China	0.00	66.69	66.69	66.69	66.69	66.69
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	1.14	1.14	1.14	1.14	1.14
India	0.00	7.58	7.58	7.58	7.58	7.58
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	3.80	3.80	3.80	3.80	3.80
Non-OECD Annex I	0.00	0.66	0.66	0.66	0.66	0.66
OECD	0.00	35.41	35.41	35.41	35.41	35.41
Russian Federation	0.00	0.66	0.66	0.66	0.66	0.66
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	25.00	25.00	25.00	25.00	25.00
World Total	0.00	110.78	110.78	110.78	110.78	110.78

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 8-6: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	23.82	23.82	23.82	23.82	23.82
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.20	0.20	0.20	0.20	0.20
China	0.00	86.43	86.43	86.43	86.43	86.43
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.67	0.67	0.67	0.67	0.67
India	0.00	8.72	8.72	8.72	8.72	8.72
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	4.10	4.10	4.10	4.10	4.10
Non-OECD Annex I	0.00	0.30	0.30	0.30	0.30	0.30
OECD	0.00	33.62	33.62	33.62	33.62	33.62
Russian Federation	0.00	0.30	0.30	0.30	0.30	0.30
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	22.84	22.84	22.84	22.84	22.84
World Total	0.00	129.51	129.51	129.51	129.51	129.51

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 8-7: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	8.72	8.72	8.72	8.72	8.72
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.19	0.19	0.19	0.19	0.19
China	0.00	23.50	23.50	23.50	23.50	23.50
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.00	0.00	0.00	0.00	0.00
India	0.00	0.74	0.74	0.74	0.74	0.74
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	0.06	0.06	0.06	0.06	0.06
Non-OECD Annex I	0.00	0.66	0.66	0.66	0.66	0.66
OECD	0.00	12.18	12.18	12.18	12.18	12.18
Russian Federation	0.00	0.66	0.66	0.66	0.66	0.66
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	8.06	8.06	8.06	8.06	8.06
World Total	0.00	37.52	37.52	37.52	37.52	37.52

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 8-8: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for HFC-23 Emissions from HCFC-22 Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	7.66	7.66	7.66	7.66	7.66
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.20	0.20	0.20	0.20	0.20
China	0.00	43.24	43.24	43.24	43.24	43.24
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.00	0.00	0.00	0.00	0.00
India	0.00	1.89	1.89	1.89	1.89	1.89
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	0.35	0.35	0.35	0.35	0.35
Non-OECD Annex I	0.00	0.30	0.30	0.30	0.30	0.30
OECD	0.00	12.32	12.32	12.32	12.32	12.32
Russian Federation	0.00	0.30	0.30	0.30	0.30	0.30
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	7.36	7.36	7.36	7.36	7.36
World Total	0.00	58.19	58.19	58.19	58.19	58.19

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 8-9: World Breakeven Costs and Emissions Reductions in 2020—No-Action Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Thermal oxidation (new plants)	\$0.23	\$0.23	21.72	15.8%	21.72	15.8%
Thermal oxidation (existing plants)	\$0.28	\$0.35	107.80	78.4%	129.51	94.2%

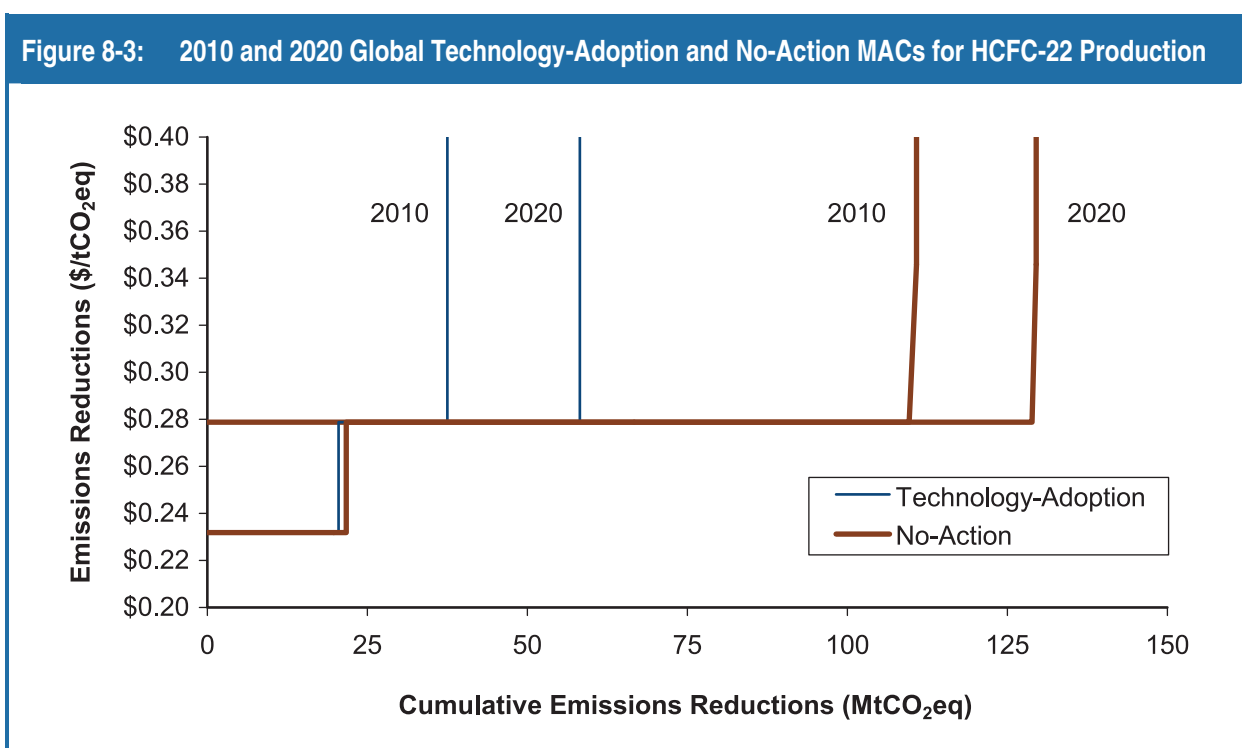
Table 8-10: World Breakeven Costs and Emissions Reductions in 2020—Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Thermal oxidation (new plants)	\$0.23	\$0.23	20.49	31.0%	20.49	31.0%
Thermal oxidation (existing plants)	\$0.28	\$0.35	37.70	57.0%	58.19	87.9%

IV.8.3.2 Global and Regional MACs and Analysis

This section discusses the results from the MAC analysis of the world and selected countries and regions, including China, Japan, the United States, the EU-15, other OECD, and the rest of the world.

Figure 8-3 presents the 2010 and 2020 global technology-adoption and no-action MACs for HCFC-22 production. As shown in Figure 8-3, the MACs include different cost points depending on the scenario and year. The 2020 no-action MAC includes all three cost points: \$0.35/tCO₂eq for thermal oxidation in the EU-15, \$0.28/tCO₂eq for thermal oxidation at all existing plants in all other regions, and \$0.23/tCO₂eq for thermal oxidation at new plants, which are assumed to exist only in developing countries in 2020. The 2010 MACs omit the cost point for thermal oxidation at new plants because no new plants are assumed to be built until after 2010. Similarly, the technology-adoption MACs exclude the cost point for thermal oxidation in the EU because the EU is assumed to have fully implemented thermal oxidation in the baseline in the technology-adoption scenario. Costs (in terms of \$/tCO₂eq) are slightly higher in EU-15 than in other parts of the world because this analysis uses EU-specific values for capital costs and average emissions per facility, which together result in a slightly higher calculated cost per tCO₂eq.

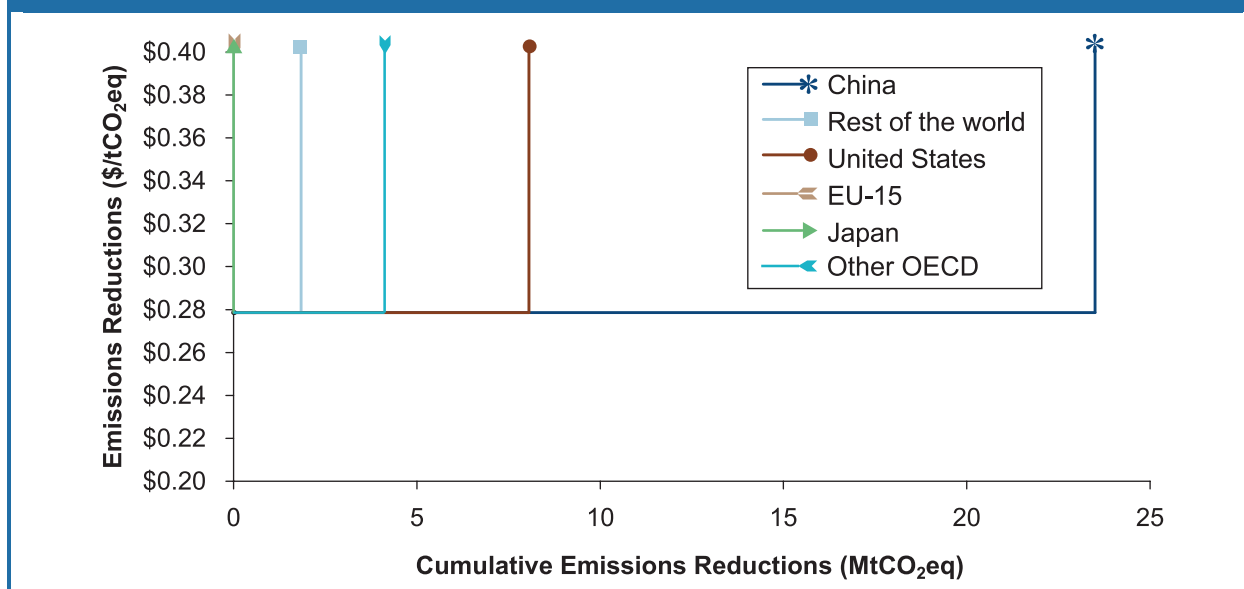


As shown in Figure 8-3, in the no-action scenario, HCFC-22 production offers global emissions reductions of about 111 MtCO₂eq and 130 MtCO₂eq in 2010 and 2020, respectively. The 17 percent increase in emissions reductions between 2010 and 2020 is a result of baseline emissions increases in developing countries, mainly China, between 2010 and 2020. Option costs are not assumed to vary between 2010 and 2020; therefore, the additional emissions abatable in 2020 shifts the 2020 MAC slightly to the right compared to the 2010 MAC.

In the technology-adoption scenario, HCFC-22 production offers global emissions reductions of about 38 MtCO₂eq and 58 MtCO₂eq in 2010 and 2020, respectively. Available reductions are smaller than in the no-action MAC because more emissions are reduced in the technology-adoption baseline. The 55 percent

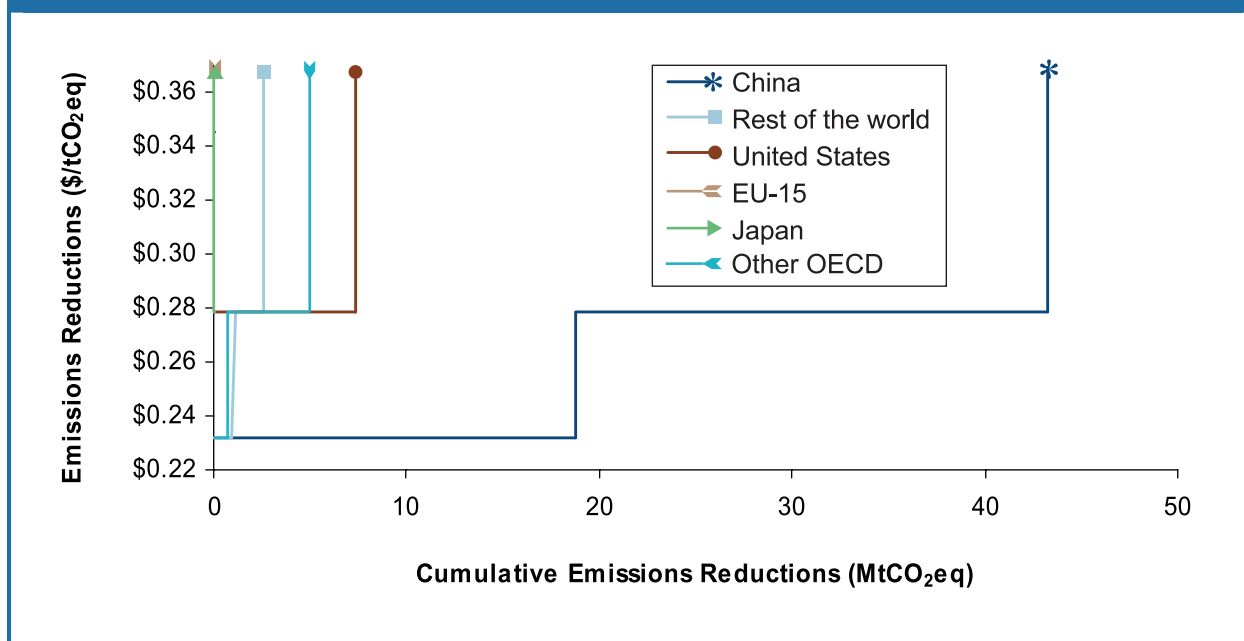
increase in emissions reductions between 2010 and 2020 is, again, a result of baseline emissions increases in developing countries, mainly China, between 2010 and 2020. Figures 8-4 and 8-5 present regional MACs for 2010 and 2020 under the technology-adoption scenario.

Figure 8-4: 2010 Regional Technology-Adoption MACs



EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 8-5: 2020 Regional Technology-Adoption MACs



EU-15 = European Union; OECD = Organisation of Economic Co-operation and Development.

Large emissions reductions are available in China even in the technology-adoption scenario. These result from China's large expected production of HCFC-22, relatively high emissions rate (3 kg HFC-23/100kg HCFC-22), and incomplete adoption of thermal oxidation in the baseline. China's expected 2010 HFC-23 emissions make up more than 60 percent of total global emissions in that year, and China's reductions make up 63 percent of the total global reductions. (These percentages differ slightly because some of the emissions from other regions are residual emissions that cannot be reduced further.) U.S. reductions make up much of the remainder of available reductions because, like China, the United States is a large producer of HCFC-22 (accounting for about 20 percent of global production in 2010 and 2020) and is also assumed not to fully implement thermal abatement in the baseline. Emissions and reductions from other regions are expected to be smaller because of (1) a smaller growth rate for HCFC-22 production (this growth rate is actually negative in most developed countries because of their ongoing phaseout of most uses of HCFC-22 under the Montreal Protocol) and (2) the widespread use of abatement technologies in developed countries.

Large emissions reductions are also available for 2020 in China both in existing and new plants. China's expected 2020 HFC-23 emissions make up 72 percent of total global emissions in that year, and China's reductions make up 74 percent of the total global reductions.

IV.8.3.3 Uncertainties and Limitations

This section focuses on the uncertainties associated with the cost estimates presented in this report. Uncertainties regarding emissions estimates are discussed in the USEPA report *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020* (USEPA, 2006).

There is some uncertainty associated with the costs of thermal oxidation. Currently, costs are available for three versions of thermal oxidation based on data from the United States and the EU, respectively. For these two regions, the estimated breakeven prices are expected to be reasonably robust, an expectation that is supported by the fact that the breakeven prices for the United States and EU versions of the technology are quite similar despite significant differences in capital costs and reductions. Outside of the United States and EU, costs and breakeven prices are less certain. U.S. capital costs and annual costs were applied to all countries outside of the EU. However, these countries may be faced with higher costs from transportation and tariffs associated with purchasing the technology from abroad, or with lower costs if there is domestic production of these technologies.

The estimated cost per tCO₂eq is very sensitive to the assumed HCFC-22 production level and HFC-23 emissions rate of plants where thermal oxidation is assumed to be installed. The capital cost information used in this analysis was for an oxidation system with a 7 to 10 million Btu capacity. This capacity is large enough to oxidize HFC-23 emissions from the largest plant in the world, which has a production capacity of 100,000 tons. However, because most plants have capacities closer to 20,000 tons, this analysis uses that production as the basis for the cost estimates. This may overestimate the cost/tCO₂eq at larger plants and underestimate it at smaller plants. Similarly, this analysis conservatively uses a 2 percent emissions factor in its reduction estimates; plants with higher emissions factors rates reduce more emissions by installing thermal abatement.

Future production levels, emissions rates, and abatement levels are particularly uncertain. Future policies (e.g., under the Montreal Protocol) could affect total production of HCFC-22 and therefore emissions of HFC-23. Changing emissions rates may also have a significant impact on emissions. In the technology-adoption baseline, the USEPA assumed that currently identified CDM projects will be implemented in China, India, Korea, and Mexico. However, even after implementation of these projects, significant reduction opportunities remain, both in these countries and elsewhere. There is a significant probability that many of these emissions will be averted, either through CDM or other mechanisms. In

this case, HFC-23 emissions will be lower than projected in the technology-adoption baseline. Such a decrease in emissions would also decrease the reductions available in the technology-adoption MACs.

IV.8.4 References

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IV.9 PFC and SF₆ Emissions from Semiconductor Manufacturing

IV.9.1 Source Description

The semiconductor industry currently uses several fluorinated compounds (CF₄, C₂F₆, C₃F₈, C₄F₈, HFC-23, NF₃, and SF₆) during the fabrication process.¹ A fraction of each of these gases is emitted during two frequently used manufacturing process steps: the plasma etching of thin films and the cleaning of chemical-vapor-deposition chambers.² In addition, by-product emissions of CF₄ result when a fraction of the heavier gases consumed is converted during the manufacturing process or when F-atoms produced in a plasma react with the carbon present in certain low-dielectric strength films for CF₄. Total PFC emissions from this source vary by process and device type.³ Tables 9-1 and 9-2 present estimates of historical and forecasted semiconductor manufacturing PFC emissions for 1990 through 2020 under two different scenarios.

Table 9-1: Total PFC Emissions from Semiconductor Manufacturing (MtCO₂eq)—No-Action Baseline

Country/Region	2000	2010	2020
Africa	0.1	0.1	0.2
Annex I	17.0	47.2	74.3
Australia/New Zealand	0.0	0.0	0.1
Brazil	0.0	0.0	0.0
China	0.8	10.7	37.5
Eastern Europe	0.2	0.9	1.5
EU-15	1.9	5.3	8.5
India	0.2	0.6	1.0
Japan	7.4	11.0	15.3
Mexico	0.1	0.0	0.0
Non-OECD Annex I	0.8	1.5	2.3
OECD	19.6	59.1	98.1
Russian Federation	0.8	1.4	2.3
South & SE Asia	0.6	5.7	28.3
United States	6.4	28.2	46.1
World Total	27.4	99.2	231.9

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

¹ The chemical compound CHF₃ is more commonly referred to as HFC-23; thus, the latter term is used here.

² Very small amounts of CF₄ are emitted during a process step called *ashing* or *photoresist* stripping. Because emissions from this process are considered very small, they are not included.

³ Note that although the term “PFC” (strictly referring to only perfluorocarbon compounds) does not include all of the fluorinated compounds emitted from this source, the semiconductor industry commonly refers to the mix of fluorinated compounds as PFCs; this report adopts the same convention.

Table 9-2: Total PFC Emissions from Semiconductor Manufacturing (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2000	2010	2020
Africa	0.1	0.1	0.1
Annex I	17.0	12.9	10.7
Australia/New Zealand	0.0	0.0	0.0
Brazil	0.0	0.0	0.0
China	0.8	10.7	7.1
Eastern Europe	0.2	0.9	0.6
EU-15	1.9	1.2	1.2
India	0.2	0.6	0.4
Japan	7.4	3.7	3.7
Mexico	0.1	0.0	0.0
Non-OECD Annex I	0.8	1.5	1.0
OECD	19.6	13.8	12.1
Russian Federation	0.8	1.4	1.0
South & SE Asia ^a	0.6	5.7	3.8
United States	6.4	5.5	4.1
World Total	27.4	36.9	28.3

^a Note that the region South and Southeast Asia (South & SE Asia) in the table above includes different countries than South and East Asia (S&E Asia) as defined in the *Global Anthropogenic Non-CO₂ Emissions: 1990–2020* (USEPA, 2006) and in Figure 9-1. South and East Asia in Figure 9-1 includes the major semiconductor manufacturing regions of Taiwan and South Korea, while South and Southeast Asia excludes these regions.

IV.9.1.1 Technology-Adoption Baseline

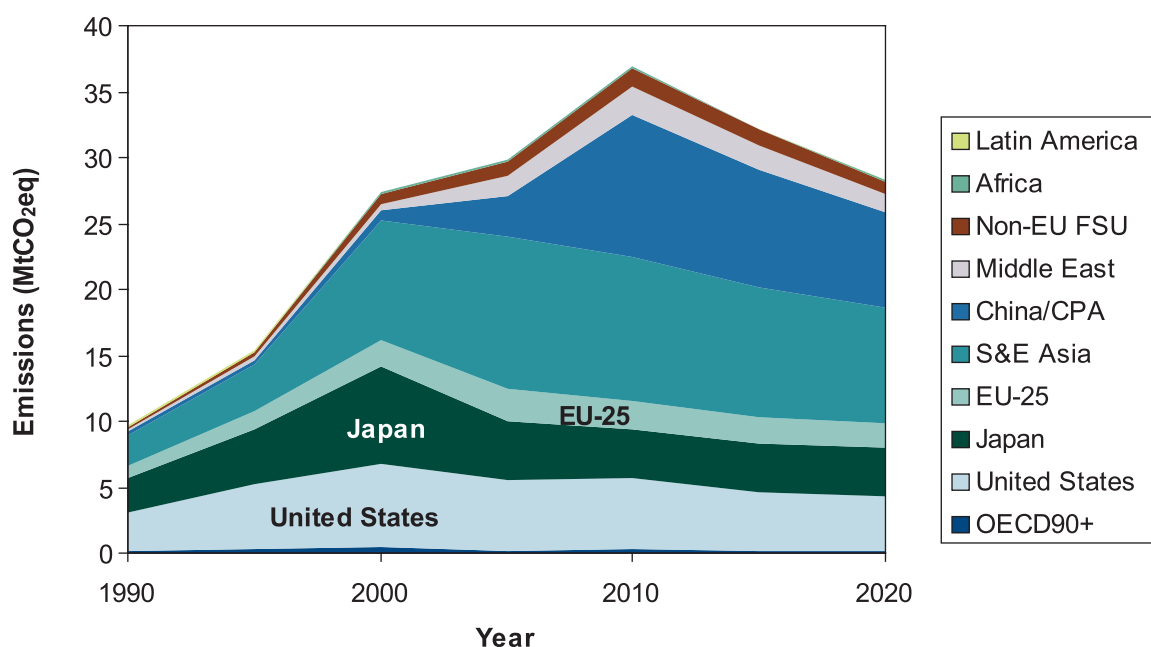
The technology-adoption baseline incorporates those reductions that have resulted or are anticipated to result from international voluntary climate commitments. In April 1999, the semiconductor manufacturing industry set an aggressive target to reduce PFC emissions. The World Semiconductor Council (WSC) then agreed to reduce PFC emissions to 10 percent below 1995 levels by the year 2010.⁴ Because WSC members then accounted for production of over 90 percent of the world's semiconductors, the goal is expected to have dramatic effects in decreasing emissions over time, which would widen the gap over time between emissions forecasts shown under the two scenarios presented in Figure 9-1 and Figure 9-2 (note that the scales are different in the two graphs).

OECD and Asia (including China/CPA and South and East Asia) regions are expected to account for the vast majority of production, and therefore also the emissions, throughout the time horizon studied. The highest-emitting countries worldwide in 2000 were Japan, the United States, Taiwan, South Korea, and Germany. By 2010 and through 2020, the highest-emitting country worldwide is expected to be China, followed by the United States, Japan, South Korea, Singapore,⁵ and Malaysia. The appearance of

⁴ The base year for South Korea is 1997.

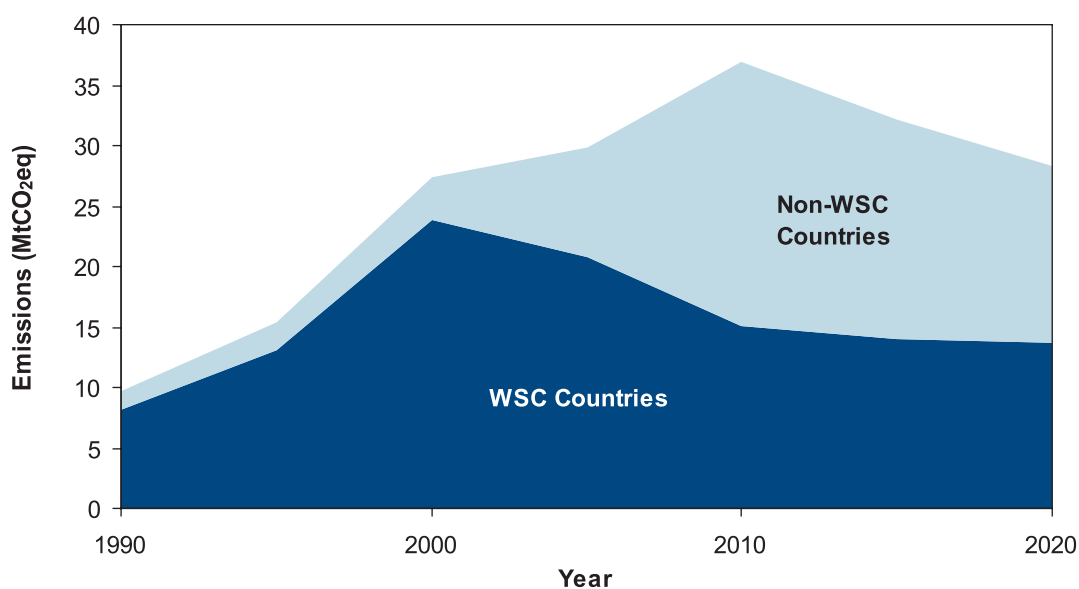
⁵ This reflects the top emitting countries in 2020, in descending order of emissions; in 2010, Singapore has greater emissions than South Korea.

Figure 9-1: PFC Emissions from Semiconductor Manufacturing Based on a Technology-Adoption Scenario—1990 through 2020 (MtCO₂eq)



CPA = Centrally Planned Asia; EU-25 = European Union; S&E Asia = South and East Asia; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development.

Figure 9-2: WSC and Non-WSC Countries' Contribution to Global PFC Emissions (MtCO₂eq)



China, Singapore, and Malaysia⁶ among the top emitting countries reflects a geographic shift in production such that the majority of future growth takes place in these countries. This reflects an industry trend toward outsourcing production to dedicated manufacturing firms, called foundries, concentrated in these countries.

Global emissions are estimated to have grown at a compound annual growth rate of 11 percent per year through the year 2000. Following the introduction of voluntary commitments and resulting mitigation efforts, however, a noticeable shift in direction is expected to occur under the technology-adoption scenario. As shown in Figure 9-1, the overall trend in OECD emissions is reflected in the emissions from the United States, the European Union (EU-25), and Japan. These regions, where most manufacturers are WSC members, are expected to achieve the WSC goal collectively by 2010. In the long run, even countries whose manufacturers have not adopted the WSC goal, such as China, Singapore, and Malaysia—countries not part of the WSC, are assumed to reduce their emissions rates as new, lower-emitting, more productive manufacturing equipment enters the global market. This expectation accounts for the reduction in emissions from China and South and East Asia between 2010 and 2020.

Figure 9-2 shows the relative distribution of global emissions under the technology-adoption scenario between WSC and non-WSC members and illustrates these trends even more clearly. Note that emissions from WSC countries peaked in 2000.

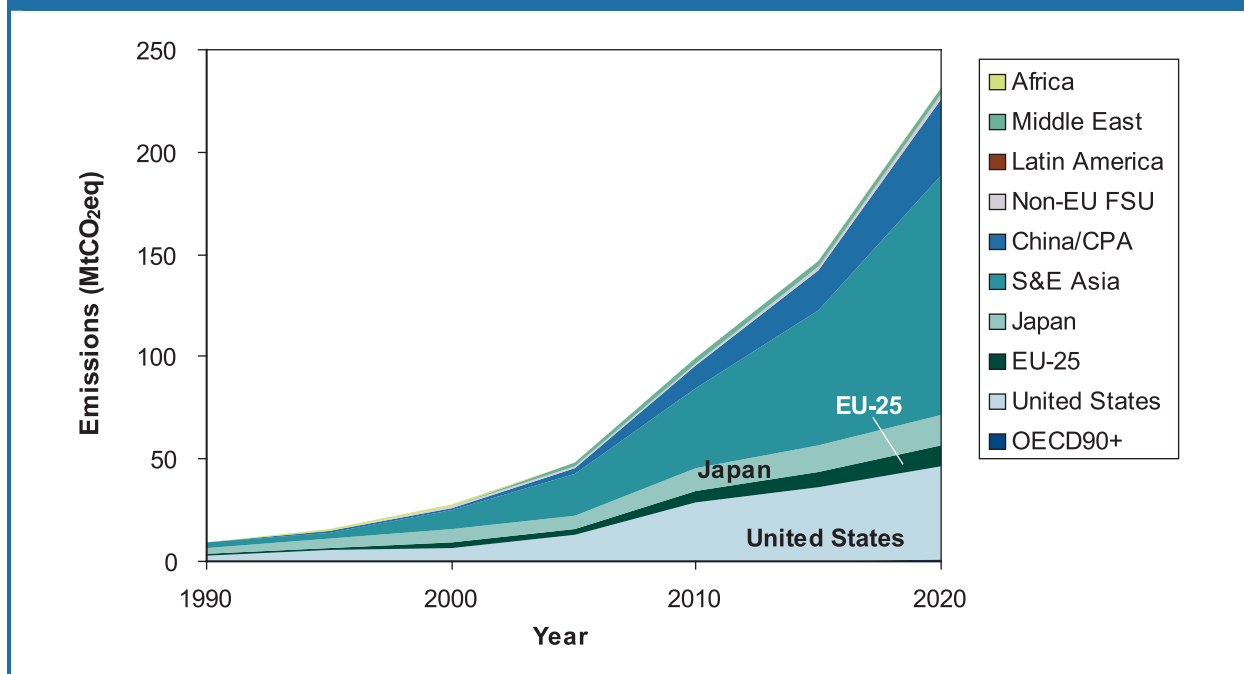
IV.9.1.2 No-Action Baseline

The no-action scenario estimates emissions that would result from normal industry activity with no emissions control measures, voluntary or regulation driven. This trajectory can be considered an upper bound and can serve as a reference level to which the alternative technology-adoption scenario emissions can be compared. The difference between these two emissions sets represents the emissions reductions achieved by semiconductor manufacturers as they implement emissions control technologies or other mitigation measures.

Figure 9-3 shows the relative distribution of global emissions under the no-action scenario. As in the technology-adoption scenario, the OECD and Asia regions are expected to remain the largest emitters throughout the time horizon studied; emissions from these two regions (including OECD90+, China/CPA, and South and East Asia) combined are expected to make up 98 percent of global emissions in 2020.

Historical trends are the same as those presented for the technology-adoption baseline, including the 11 percent per year annual growth through 2000. However, in the no-action baseline, this high annual growth continues virtually unabated through 2010 and is particularly pronounced in Asia beyond 2010. In these countries, most notably China, Singapore, and Malaysia, semiconductor manufacturing is assumed to increase significantly, as discussed above in the no-action baseline, contributing to higher emissions over the time horizon presented. Beyond 2010, the growth rate is assumed to decline by one-half, reflecting slower growth in demand for semiconductors. Nevertheless, global emissions are expected to continue to climb substantially, reaching 232 MtCO₂eq by 2020.

⁶ As of May 2006, China, Singapore, and Malaysia have not joined the WSC.

Figure 9-3: PFC Emissions from Semiconductor Manufacturing Based on a No-Action Scenario—1990 through 2020 (MtCO₂eq)

CPA = Centrally Planned Asia; EU-25 = European Union; S&E Asia = South and East Asia; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development.

IV.9.2 Cost of PFC and SF₆ Emissions Reduction from Semiconductor Manufacturing

IV.9.2.1 Abatement Options

Overview of Options and Analysis

This analysis considers six different emissions reduction technologies applicable to semiconductor manufacturing. These options are shown in Tables 9-3 through 9-8 below. The five main characteristics that determine the reductions achieved by each technology in each scenario are (1) whether the technology is applicable to plasma etch processes, chemical vapor deposition (CVD) chamber cleaning processes, or both; (2) the maximum share of the etch or clean market that is assumed to be claimed by the technology relative to a baseline with no preexisting emissions controls; (3) the share of the etch or clean market that is already claimed by the technology in the baseline of concern; (4) the reduction efficiency of the technology; that is, the percentage by which the technology reduces the emissions stream to which it is applied; and (5) for non-WSC countries, the year, because only a fraction of the full reductions are assumed to be available to these countries in 2010. Of these characteristics, (4) and sometimes (1) affect the cost per tCO₂eq of the technology's reductions, while all five characteristics affect the size and shape of the aggregate MACs.

In general, technologies applicable to CVD chamber cleaning achieve larger reductions than those applicable only to etch processes because CVD chamber cleaning is estimated to account for 80 percent of the emissions from semiconductor manufacturing, while etch is estimated to account for 20 percent. The maximum share of the etch or clean market has been estimated for each technology by region and year based on that technology's cost-effectiveness and applicability, industry trends, and expert judgment. The

maximum shares for the no-action scenario are shown below in Tables 9-3 and 9-4. In the no-action scenario, none of the technologies is assumed to be implemented in the baseline; thus, the market penetrations provided in Tables 9-3 and 9-4 are percentages of the total emissions in the no-action scenario for that year. That is, the percentages in Tables 9-3 and 9-4 correspond to the maximum shares described in (2) above.

Table 9-3: Maximum Market Penetrations for WSC Countries in the No-Action Baseline (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process
Thermal destruction	5%	5%
Catalytic decomposition	5%	5%
Capture/recovery	15%	15%
Plasma abatement	70%	0%
NF ₃ remote clean	0%	70%
C ₃ F ₈ replacement	0%	5%

^a Assumed market penetration of technology, presented as a percentage of no-action baseline emissions that result from etching or CVD chamber cleaning, respectively.

Table 9-4: Maximum Market Penetrations for Non-WSC Countries in the No-Action Baseline (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process	Plasma Etching Process	CVD Chamber Cleaning Process
	2010		2020	
Thermal destruction	3%	3%	7%	7%
Catalytic decomposition	3%	3%	8%	8%
Capture/recovery	2%	2%	5%	5%
Plasma abatement	30%	0%	75%	0%
NF ₃ remote clean	0%	30%	0%	75%
C ₃ F ₈ replacement	0%	2%	0%	5%

^a Assumed market penetration of technology, presented as a percentage of no-action baseline emissions that result from etching or CVD chamber cleaning, respectively.

In the technology-adoption scenario, semiconductor manufacturers are assumed to implement reduction technologies in the baseline to the extent necessary to achieve the WSC goal. Tables 9-5 and 9-7 provide the baseline market penetrations of the various technologies in the technology-adoption baseline for WSC countries and non-WSC countries, respectively. To estimate the emissions reductions remaining in the technology-adoption MACs after implementing the technologies shown in Tables 9-5 and 9-7, the shares in Tables 9-5 and 9-7 are subtracted from the corresponding shares in Tables 9-3 and 9-4. The resulting percentages are then recast in terms of the emissions that remain unabated in the technology-adoption baseline. (These are different from the total emissions because the technology-adoption baseline includes residual emissions from emissions streams to which technologies have already been applied.) For example, to obtain the market share for remote clean in the WSC in the 2010 technology-adoption baseline, the 57 percent in Table 9-5 is subtracted from the 70 percent in Table 9-3, and the difference is then divided by 14 percent, the sum of the remaining, unused shares for the technologies applicable to CVD chamber cleaning. These results are shown in Tables 9-6 (for WSC countries) and 9-8 (for non-WSC countries).

Table 9-5: Baseline Market Penetrations for WSC Countries in the Technology-Adoption Baseline (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process	Plasma Etching Process	CVD Chamber Cleaning Process
	2010		2020	
Thermal destruction	4%	5%	4.8%	5.0%
Catalytic decomposition	5%	5%	5.0%	5.0%
Capture/recovery	15%	15%	15.0%	15.0%
Plasma abatement	57%	0%	67.2%	0.0%
NF ₃ remote clean	0%	57%	0.0%	67.2%
C ₃ F ₈ replacement	0%	4%	0.0%	4.8%

^a Assumed market penetration of technology, presented as a percentage of no-action baseline emissions that result from etching or CVD chamber cleaning, respectively.

Table 9-6: Maximum Market Penetrations for WSC Countries in the Technology-Adoption Baseline (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process	Plasma Etching Process	CVD Chamber Cleaning Process
	2010		2020	
Thermal destruction	5%	0%	3%	0%
Catalytic decomposition	0%	0%	0%	0%
Capture/recovery	0%	0%	0%	0%
Plasma abatement	69%	0%	35%	0%
NF ₃ remote clean	0%	93%	0%	93%
C ₃ F ₈ replacement	0%	7%	0%	7%

^a Assumed market penetration of technology, presented as a percentage of the technology-adoption baseline emissions from etching or CVD chamber cleaning that remain available for abatement.

Table 9-7: Baseline Market Penetrations for Non-WSC Countries in the Technology-Adoption Baseline in 2020 (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process
Thermal destruction	6%	7%
Catalytic decomposition	8%	8%
Capture/recovery	5%	5%
Plasma abatement	62%	0%
NF ₃ remote clean	0%	62%
C ₃ F ₈ replacement	0%	4%

^a Assumed market penetration of technology, presented as a percentage of no-action baseline emissions that result from etching or CVD chamber cleaning, respectively.

Table 9-8: Maximum Market Penetrations for Non-WSC Countries in the Technology-Adoption Baseline (Percent)^a

Option	Plasma Etching Process	CVD Chamber Cleaning Process	Plasma Etching Process	CVD Chamber Cleaning Process
	2010		2020	
Thermal destruction	3%	3%	6%	0%
Catalytic decomposition	3%	3%	0%	0%
Capture/recovery	2%	2%	0%	0%
Plasma abatement	30%	0%	68%	0%
NF ₃ remote clean	0%	30%	0%	94%
C ₃ F ₈ replacement	0%	2%	0%	6%

^a Assumed market penetration of technology, presented as a percentage of the technology-adoption baseline emissions from etching or CVD chamber cleaning that remain available for abatement.

For WSC countries, the full reductions from each technology are assumed to be available in 2010, as shown in Table 9-3. For non-WSC countries, only 40 percent of the full reductions are assumed to be available in 2010, but this percentage grows to 100 percent in 2020, as shown in Table 9-4.

NF₃ Remote Clean Technology

The NF₃ Remote Clean system is used to abate emissions from the chemical vapor deposition (CVD) chamber cleaning process and is assumed to be applicable to all fabrication facilities. As noted above, CVD chamber cleaning emissions are reported to constitute approximately 80 percent of all semiconductor emissions. The system dissociates NF₃ using argon gas, converting the source gas to active F-atoms in the plasma, upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of Remote Clean include HF, F₂, and other gases, of which all but F₂ are removed by facility acid scrubber systems.

This analysis assumes that the emissions reduction efficiency of this option is 95 percent. The assumed maximum market penetrations of this option for WSC member countries and non-WSC countries in the no-action baseline and technology-adoption baseline are presented in Tables 9-3 through 9-8.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** Facilities moving to an NF₃ Remote Clean system are assumed to face a purchase and installation capital cost of \$59,900 per chamber (Burton, 2003a).
- **Annual Costs.** Facilities operating NF₃ Remote Clean systems are assumed to pay annual fees of \$11,000 per chamber for a preventative maintenance kit (Burton, 2003a) and to incur additional costs equal to the difference in price between NF₃ and C₂F₆. Accounting for the amount of gases used and their relative prices, an annual cost of \$3,800 per chamber is assumed (Burton, 2003a). Therefore, net annual costs are assumed to total \$14,800 per chamber.
- **Cost Savings.** Facilities that install NF₃ Remote Clean systems achieve chamber-cleaning times that are 30 to 50 percent faster than baseline C₂F₆ cleaning times (International SEMATECH, 1999) and decrease the number of cleanings between wafer passes. The end result is an increase in the time devoted to the actual manufacturing portion of the process, which allows high-utilization facilities to recoup their capital costs in an estimated 9 months or less. Because of this

process improvement, assuming a 9-month capital return, it can be calculated that facilities receive a cost savings of one and one-third times the capital cost, or \$79,867 per chamber, on an annual basis. (Burton, 2003b).

C₃F₈ Replacement

C₃F₈ replacement is used to abate emissions from the CVD chamber cleaning process and is assumed to be applicable to all fabrication facilities. The C₃F₈ simply replaces C₂F₆, which reduces emissions because C₂F₆ has a 100-year global warming potential (GWP) of 9,200, whereas C₃F₈ has a 100-year GWP of 7,000 and an atmospheric lifetime that is less than one-third that of C₂F₆ (IPCC, 1996). In addition, C₃F₈ is more efficiently used/consumed during CVD chamber cleaning than C₂F₆ (and produces about the same amount of CF₄ during cleaning), which, combined with the differences in GWP, yields an assumed emissions reduction efficiency of 85 percent. The assumed maximum market penetrations for WSC and non-WSC countries under the no-action and technology-adoption scenarios are presented in Tables 9-3 through 9-8.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** Because the C₃F₈ simply replaces the C₂F₆, it is assumed that facilities do not incur any capital costs (Burton, 2003a).
- **Annual Costs.** The cost of C₃F₈ is assumed to equal the cost of C₂F₆, so the replacement results in no annual costs (Burton, 2003a).
- **Cost Savings.** It is assumed that no cost savings are associated with this technology.

Point-of-Use Plasma Abatement

The Point-of-Use Plasma Abatement system is used to abate emissions from the plasma etching process and is assumed to be applicable to all fabrication facilities. Plasma etching emissions constitute 20 percent of all semiconductor emissions. The system uses a small plasma source that effectively dissociates the PFC molecules that react with fragments of the additive gas—H₂, O₂, H₂O, or CH₄—in order to produce low-molecular-weight by-products such as HF with little or no GWP. After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of PFC molecules (Motorola, 1998). The evaluations performed to date indicate no apparent interference with the etch process.

This analysis assumes that the emissions reduction efficiency of this option is 95 percent. The assumed maximum market penetrations for WSC and non-WSC countries under the no-action and technology-adoption scenarios are presented in Tables 9-3 through 9-8.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** It is assumed that plasma abatement technology requires capital costs of \$35,000 per etching chamber, which covers the purchase and installation of the system (Burton, 2003a).
- **Annual Costs.** Facilities with plasma abatement technology are assumed to incur an annual \$1,000 operational expense per etch chamber (Burton, 2003a).
- **Cost Savings.** It is assumed that there are no cost savings associated with this technology.

Capture/Recovery

The capture/recovery membrane is used to abate emissions from both the plasma etching and CVD chamber cleaning processes and is assumed to be applicable to all fabrication facilities. The capture/recovery membrane separates unreacted and/or process-generated PFCs from other gases for

further processing. The treatment process allows for the possibility of some reuse of the captured PFC gas (Mocella, 1998). These capture/recovery systems can either reprocess the PFC for reuse or they can concentrate the gas for subsequent off-site disposal. Because reprocessing inevitably produces PFC gas that is less pure than virgin PFCs, semiconductor process engineers have little or no interest in reusing the gas for fear of the possible process-harming impurities (Burton, 2003b). The lack of interest in PFC reuse for semiconductor manufacturing combines with the lack of market for reprocessed PFC gas outside the industry to make destruction highly attractive (Mocella, 1998; Burton, 2003b). Although a few companies have installed pilot PFC capture/recovery systems, this technology is reported to be unattractive if NF_3 cleaning systems are used, because such cleaning processes do not leave sufficient PFCs in the stream to make gas recovery economically viable. In general, removal efficiencies for C_2F_6 , CF_4 , SF_6 , and C_3F_8 are in the high 90s, whereas CHF_3 and NF_3 removal efficiencies fall between 50 percent and 60 percent.

This analysis assumes that the overall emissions reduction efficiency of this option is 96 percent (International SEMATECH, 1999). The assumed maximum market penetrations for WSC and non-WSC countries under the no-action and technology-adoption scenarios are presented in Tables 9-3 through 9-8.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** Because the equipment is leased, capital costs associated with a capture/recovery membrane include only installation and structural changes for preparing the facility and its individual chambers for the membrane system. This analysis assumes that total capital costs are \$1,105,000 per facility, assuming that a standard facility has 200 chambers with a 4-to-1 ratio of etch chambers to CVD chambers (Burton, 2003a).
- **Annual Costs.** Facilities are assumed to lease the equipment and an operator for an annual cost of \$300,000 (Burton, 2003a). Additionally, they are assumed to incur annual utility charges, which encompass gas destruction, water, electricity, and all other costs, of \$60,000—for a total annual cost of \$360,000 per facility.
 - **Cost Savings.** It is assumed that there are no cost savings associated with this technology.

Catalytic Decomposition System

The catalytic decomposition system is used to abate emissions from both the plasma etching and CVD chamber cleaning processes and is assumed to be applicable to all fabrication facilities. Catalytic decomposition systems are installed in the process after the turbo pump, which dilutes the exhaust stream prior to feeding it through the scrubber and emitting the scrubbed gases into the atmosphere. Consequently, there is no back flow into the etching tool itself that could adversely affect the performance of the etching tool. Because catalytic destruction systems operate at low temperatures, they also produce little or no NO_x emissions and they demand low volumes of water. Although the technology is applicable at all fabrication facilities, off-the-shelf systems must be stream- or process-specification-specific, built to reflect a certain minimum concentration and flow of PFC within the exhaust stream.

This analysis assumes that the emissions reduction efficiency of this option is 99 percent (International SEMATECH, 1999). The assumed maximum market penetrations for WSC and non-WSC countries under the no-action and technology-adoption scenarios are presented in Tables 9-3 through 9-8.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** The purchase and installation capital costs associated with a catalytic decomposition system are assumed to total \$250,000 per every four etching chambers (Burton, 2003a).

- **Annual Costs.** It is assumed that facilities incur annual costs totaling \$19,750 per every four etching chambers (Burton, 2003a). These costs are assumed to cover annual waste discharge treatments, catalyst replacements, and utility charges.
- **Cost Savings.** It is assumed that no cost savings are associated with this technology.

Thermal Destruction/Thermal Processing Units (TPU)

The thermal destruction system is used to abate emissions from both the plasma etching and CVD chamber cleaning processes and is assumed to be applicable to all fabrication facilities. Thermal destruction technology is advantageous because it does not affect the manufacturing process (Applied Materials, 1999). However, the combustion devices use significant amounts of cooling water, which requires treatment as industrial wastewater. Finally, thermal oxidation may also produce NO_x emissions, which are regulated air pollutants.

This analysis assumes that the emissions reduction efficiency of this option is 97 percent. The increase in other greenhouse gas emissions, both from the process-related burning of natural gas and from the electricity demand, may reduce the efficiency of this option (Burton, 2003a). Future analysis could be conducted to quantify the net reduction efficiency, which is expected to be closer to 90 percent (Burton, 2003a). The assumed maximum market penetrations for WSC and non-WSC countries under the no-action and technology-adoption scenarios are presented in Tables 9-3 through 9-6.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** Thermal decomposition systems are assumed to require capital costs totaling \$189,850 per every four etching chambers, which covers the purchase of the system, installation, natural gas costs, and the installation of a water circulation unit (Burton, 2003a).
- **Annual Costs.** It is assumed that facilities incur annual costs of \$11,100 per every four etching chambers to cover system maintenance, waste disposal, and input purchases (Burton, 2003a).
- **Cost Savings.** It is assumed that no cost savings are associated with this technology.

IV.9.3 Results

IV.9.3.1 Data Tables and Graphs

Tables 9-9 through 9-12 provide a summary of semiconductor manufacturing emissions reductions at a 10 percent discount rate and 40 percent tax rate by cost per metric ton of carbon dioxide equivalent (tCO₂eq) for various countries/regions of the world in 2010 and 2020 under the no-action and technology-adoption scenarios. Table 9-13 and 9-14 provide a breakdown of the costs associated and the global emissions reductions associated with implementing each abatement option under the two baseline scenarios in 2020.

IV.9.3.2 Global and Regional MACs and Analysis

Global Trends

This section discusses the results from the MAC analysis of the world and selected countries/regions. In the technology-adoption scenario, which is based on the assumption that World Semiconductor Council manufacturers meet their global goal of reducing emissions to 90 percent of 1995 levels by 2010, worldwide emissions reductions of up to 18.3 MtCO₂eq are available in 2010 at a cost below \$25/tCO₂eq. In 2020, global reductions of 14.5 MtCO₂eq are available at the same cost. In both years, significant

Table 9-9: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.0	0.0	0.1	0.1	0.1	0.1
Annex I	25.9	32.4	40.7	43.0	43.0	43.0
Australia/New Zealand	0.0	0.0	0.0	0.0	0.0	0.0
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
China	2.6	2.8	3.7	4.0	4.0	4.0
Eastern Europe	0.3	0.3	0.4	0.4	0.4	0.4
EU-15	3.0	3.7	4.7	5.0	5.0	5.0
India	0.2	0.2	0.2	0.2	0.2	0.2
Japan	6.2	7.8	9.8	10.3	10.3	10.3
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Non-OECD Annex I	0.4	0.4	0.5	0.6	0.6	0.6
OECD	33.1	41.5	52.1	55.0	55.0	55.0
Russian Federation	0.4	0.4	0.5	0.5	0.5	0.5
South & SE Asia	1.4	1.5	2.0	2.1	2.1	2.1
United States	16.0	20.0	25.2	26.6	26.6	26.6
World Total	49.3	61.0	76.9	81.5	81.5	81.5

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Table 9-10: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.1	0.1	0.2	0.2	0.2	0.2
Annex I	42.2	52.5	66.1	69.9	69.9	69.9
Australia/New Zealand	0.0	0.0	0.1	0.1	0.1	0.1
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
China	22.6	24.4	32.3	35.3	35.3	35.3
Eastern Europe	0.9	1.0	1.3	1.4	1.4	1.4
EU-15	4.8	6.0	7.6	8.0	8.0	8.0
India	0.6	0.6	0.9	0.9	0.9	0.9
Japan	8.7	10.9	13.7	14.4	14.4	14.4
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Non-OECD Annex I	1.4	1.5	2.0	2.2	2.2	2.2
OECD	55.6	69.6	87.4	92.4	92.4	92.4
Russian Federation	1.4	1.5	2.0	2.2	2.2	2.2
South & SE Asia	17.1	18.4	24.4	26.6	26.6	26.6
United States	26.1	32.7	41.1	43.4	43.4	43.4
World Total	134.0	160.4	204.6	218.2	218.2	218.2

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Table 9-11: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.0	0.0	0.1	0.1	0.1	0.1
Annex I	6.7	6.8	8.1	8.2	8.2	8.2
Australia/New Zealand	0.0	0.0	0.0	0.0	0.0	0.0
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
China	2.6	2.8	3.7	4.0	4.0	4.0
Eastern Europe	0.2	0.2	0.3	0.3	0.3	0.3
EU-15	0.7	0.7	0.8	0.8	0.8	0.8
India	0.2	0.2	0.2	0.2	0.2	0.2
Japan	2.2	2.2	2.6	2.6	2.6	2.6
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Non-OECD Annex I	0.4	0.4	0.5	0.6	0.6	0.6
OECD	7.7	7.8	9.2	9.3	9.3	9.3
Russian Federation	0.4	0.4	0.5	0.5	0.5	0.5
South & SE Asia	1.4	1.5	2.0	2.1	2.1	2.1
United States	3.2	3.2	3.8	3.8	3.8	3.8
World Total	14.4	14.8	18.3	19.0	19.0	19.0

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Table 9-12: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.1	0.1	0.1	0.1	0.1	0.1
Annex I	3.7	3.7	4.1	4.1	4.1	4.1
Australia/New Zealand	0.0	0.0	0.0	0.0	0.0	0.0
Brazil	0.0	0.0	0.0	0.0	0.0	0.0
China	4.2	4.2	5.0	5.0	5.0	5.0
Eastern Europe	0.4	0.4	0.4	0.4	0.4	0.4
EU-15	0.4	0.4	0.4	0.4	0.4	0.4
India	0.2	0.2	0.3	0.3	0.3	0.3
Japan	1.1	1.1	1.2	1.2	1.2	1.2
Mexico	0.0	0.0	0.0	0.0	0.0	0.0
Non-OECD Annex I	0.6	0.6	0.7	0.7	0.7	0.7
OECD	3.8	3.8	4.2	4.2	4.2	4.2
Russian Federation	0.6	0.6	0.7	0.7	0.7	0.7
South & SE Asia	2.2	2.2	2.7	2.7	2.7	2.7
United States	1.2	1.2	1.3	1.3	1.3	1.3
World Total	12.5	12.5	14.5	14.5	14.5	14.5

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Table 9-13: Emissions Reduction and Costs in 2020—No-Action Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Remote clean	–\$67.06	–\$67.06	126.1	54.4%	126.1	54.4%
C ₃ F ₈ replacement	\$0.00	\$0.00	7.9	3.4%	134.0	57.8%
Capture/recovery (membrane)	\$4.96	\$4.96	26.4	11.4%	160.4	69.2%
Plasma abatement (etch)	\$16.83	\$16.83	31.5	13.6%	191.9	82.8%
Thermal abatement	\$24.34	\$24.34	12.7	5.5%	204.6	88.2%
Catalytic abatement	\$33.17	\$33.17	13.7	5.9%	218.2	94.1%

Table 9-14: Emissions Reduction and Costs in 2020—Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Remote clean	–\$67.06	–\$67.06	13.6	41.7%	11.8	41.7%
C ₃ F ₈ replacement	\$0.00	\$0.00	0.8	2.5%	12.5	44.2%
Capture/recovery (membrane)	\$4.96	\$4.96	0.4	0.0%	12.5	44.2%
Plasma abatement (etch)	\$16.83	\$16.83	2.8	6.3%	14.3	50.5%
Thermal abatement	\$24.34	\$24.34	0.7	0.6%	14.5	51.1%
Catalytic abatement	\$33.17	\$33.17	0.7	0.0%	14.5	51.1%

reductions can be achieved at breakeven costs less than or equal to \$0/tCO₂eq: 14.4 MtCO₂eq in 2010 and 12.5 MtCO₂eq in 2020, through implementation of the Remote Clean and C₃F₈ Replacement options. The reductions available in 2020 are smaller than those available in 2010 because both the WSC countries and especially the non-WSC countries are assumed to increase their implementation of reduction technologies between 2010 and 2020. These reduction efforts outpace production growth, leading to a decline in emissions in the technology-adoption baseline.

In the no-action MAC, under which no mitigation efforts are expected to have been implemented in the baseline, available reductions are significantly higher, rising to 81.5 MtCO₂eq in 2010 and 218.2 MtCO₂eq in 2020. Of these reductions, over half (49.3 and 134.0 MtCO₂eq, respectively) can be achieved at \$/tCO₂eq values less than or equal to \$0/tCO₂eq. In the no-action scenario, available reductions rise in proportion to increased semiconductor production.

The semiconductor manufacturing industry is treated by this analysis as a global market; the costs of mitigation are therefore not expected to differ among manufacturing countries. Thus, each global MAC curve has just six cost points.

Regional Trends in the Technology-Adoption Scenario

Figures 9-4 and 9-5 present 2010 and 2020 regional MACs for China, Japan, the United States, the EU-15, other OECD, and Rest of World for the technology-adoption scenario. China, followed by the United States, accounts for the largest available reductions of any single country in 2010. Chinese emissions are driven by China's significant share of global production and especially by the assumption that China, like other countries outside the WSC, does not implement reduction technologies until after 2010 in the technology-adoption scenario. Similarly, U.S. emissions are driven by the assumptions that the United States accounts for 25 percent of global production in 2010 (the largest share of any country in that year) and that the U.S. manufacturers that have not committed to the WSC goal (representing approximately 20 percent of U.S. production) will not meet it in 2010. The aggregate Rest of World region shows the largest quantity of emissions reductions available in 2010, largely because this region includes Taiwan, South Korea, Singapore, and Malaysia, which collectively account for approximately 30 percent of global semiconductor production in 2010.

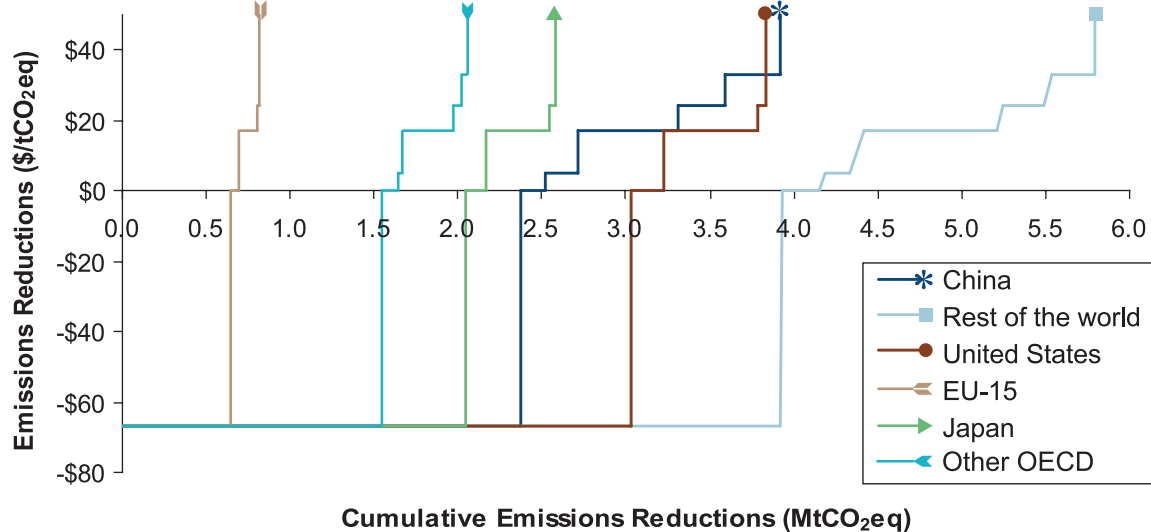
In 2020, the emissions reductions available in China grow slightly, whereas those available in the Rest of World region remain fairly constant, and those available in the other regions decrease. Although baseline emissions from Japan, the United States, the EU-15, and other OECD countries change little between 2010 and 2020 in the technology-adoption scenario, the reductions available to these countries decrease significantly because more of these reductions are assumed to be implemented in the baseline. This can be seen by comparing the 2010 and 2020 baseline market penetrations in Table 9-5 above.

Although Chinese baseline emissions decline from 2010 to 2020, potential reductions grow because the market penetration of the abatement technologies increases as technologies become fully available in countries outside the WSC. This trend is shown in Table 9-4. For the rest of the world region, which is composed of both WSC members (Taiwan and South Korea) and non-WSC members (Malaysia and Singapore), the decreases in reductions in the WSC counteract the increases in reductions elsewhere, keeping available emissions reductions relatively constant from 2010 to 2020.

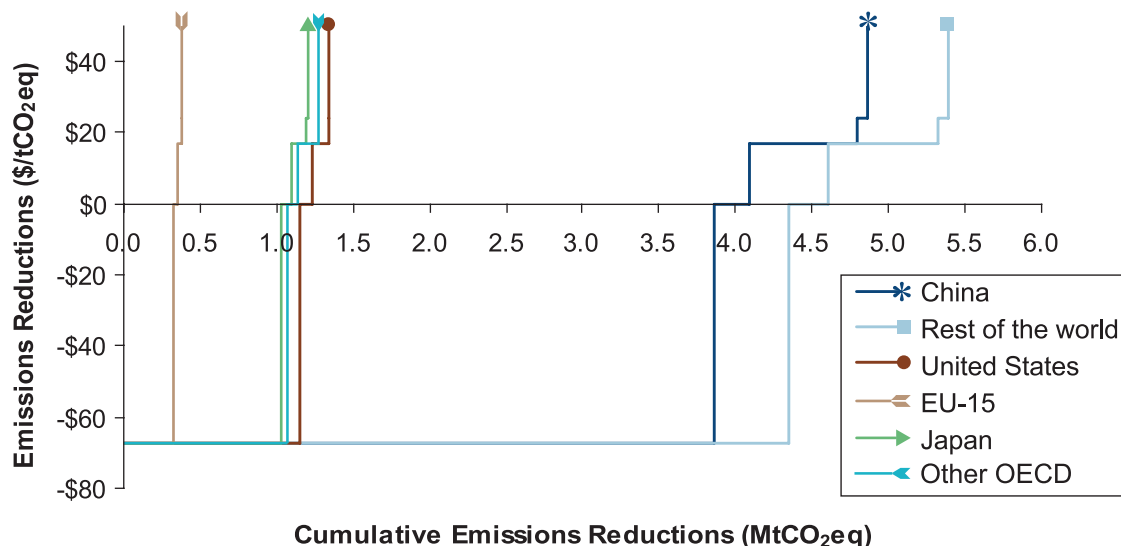
IV.9.3.3 Uncertainties and Limitations

The costs and savings presented in the above section are specific to individual technologies that represent potential emissions mitigation options for the semiconductor manufacturing industry. The assumptions that form the basis for these figures rely upon expert review of several options that were believed to be favored by industry at the time of review. Discussions with industry scientists and analysts contributed to capital and operating cost figures and were conducted in mid-2003.

Considering the rapid growth that characterizes the semiconductor manufacturing industry, it is possible that both the relative and absolute costs of some options have changed over the last 3 years. For the most part, the USEPA believes that recent changes will not change the relative ranking of the options in the market. However, capture/recovery may be an exception to this. Capture/recovery, while technologically feasible, also appears to present PFC cost and manufacturing risks that managers and process engineers appear unwilling to take. Qualitatively, this suggests that more catalytic and thermal decomposition abatement technology might be adopted than indicated in the tables and discussions in this section. Further research might provide information for updating both the maximum market penetrations and the baseline market penetrations that were assumed to apply in the technology-adoption baseline (see Tables 9-2 through 9-8).

Figure 9-4: 2010 Regional Technology-Adoption MACs for Semiconductor Manufacturing

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Figure 9-5: 2020 Regional Technology-Adoption MACs for Semiconductor Manufacturing

EU-15 = European Union; OECD90+ = Organisation for Economic Co-operation and Development.

Capital and operating costs in the United States were assumed to apply to all semiconductor manufacturing countries. This simple assumption is supported by the fact that the semiconductor manufacturing industry represents a global market with relatively few international suppliers of equipment and technology. Because fabrication facilities worldwide likely purchase equipment from the same few suppliers, it is assumed that their costs remain the same. This approach is therefore justified as a simplifying assumption, but it does not address any fab- or country-specific cost factors that may have

effects on costs, such as energy prices and labor costs. Further research might provide justification for country- or region-specific costs or scaling factors.

The MACs in this analysis (in terms of reduction percentages) were developed on a regional basis. That is, within the WSC, countries were assumed to have identical percentages of their baselines available for abatement in any given year and scenario. Similarly, countries outside of the WSC were assumed to have identical percentages of their baselines available for abatement, although these percentages were different from those of the WSC countries. By distinguishing between the WSC and non-WSC countries, this analysis accounts for much of the variation among countries in their emissions patterns and reduction opportunities. However, even within the WSC, some countries are expected to make deeper reductions than others to meet the WSC goal. This is because production has shifted from some countries, such as Japan, to others, such as Taiwan, since the mid- to late 1990s. Thus, in the technology-adoption baseline, this analysis may slightly underestimate the reduction opportunities that remain in Japan and overestimate those that remain in Taiwan.

IV.9.4 References

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IV.10 SF₆ Emissions from Electric Power Systems

IV.10.1 Source Description

Sulfur hexafluoride (SF₆) is a colorless, odorless, nontoxic, and nonflammable gas with a GWP that is 23,900 times that of CO₂ during a 100-year time horizon and an atmospheric lifetime of 3,200 years (USEPA, 2005). SF₆ is used as both an arc-quenching and insulating medium in electrical transmission and distribution equipment. Several factors affect SF₆ emissions from electrical equipment, including the type and age of SF₆-containing equipment and the handling and maintenance protocols used by electric utilities. Historically, approximately 20 percent of total global SF₆ sales have gone to electric power systems, where the SF₆ is believed to have been used primarily to replace emitted SF₆. Approximately 60 percent of global sales have gone to manufacturers of electrical equipment, where the SF₆ is believed to have been mostly banked in new equipment (Smythe, 2004).

SF₆ emissions from electrical equipment used in transmission and distribution systems occur through leakage and handling losses. Leakage losses can occur at gasket seals, flanges, and threaded fittings and are generally larger in older equipment. Handling emissions occur when equipment is opened for servicing, SF₆ gas analysis, or disposal. Baseline emissions estimates under both a Technology-Adoption and a no-action baseline scenario are presented in Table 10-1.

Table 10-1: Total SF₆ Emissions from Electric Power Systems (MtCO₂eq)—No-Action Baseline

Country/Region	2000	2010	2020
Africa	0.5	1.8	2.5
Annex I	20.5	27.3	28.6
Australia/New Zealand	0.3	0.8	0.8
Brazil	0.5	1.6	2.4
China	1.8	9.0	14.9
Eastern Europe	0.4	0.8	0.8
EU-15	1.9	1.9	1.9
India	0.7	2.4	3.5
Japan	0.5	0.4	0.4
Mexico	0.3	1.0	1.6
Non-OECD Annex I	1.5	3.9	3.9
OECD	19.5	25.8	28.0
Russian Federation	1.1	2.9	2.9
South & SE Asia	0.6	2.4	3.2
United States	15.0	17.6	18.9
World Total	26.8	52.3	65.8

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

IV.10.1.1 Technology-Adoption Baseline

As shown in Table 10-2, global emissions from electric power systems are believed to have fallen significantly between 1990 and 2000, based on SF₆ sales to utilities and estimated equipment retirements. This decline was due to a significant increase in the cost of SF₆ gas in the mid-1990s, which motivated electric utilities to implement better management practices to reduce their use of SF₆. However, sales of SF₆ increased by more than 37 percent between 2000 and 2003, reversing the trend (Smythe, 2004). In addition, equipment retirements (based on a 40-year equipment lifetime) are estimated to have more than doubled between 2000 and 2003. Together, these two trends resulted in an estimated 55 percent increase in global emissions between 2000 and 2003, creating emissions levels similar to those observed in 1990.

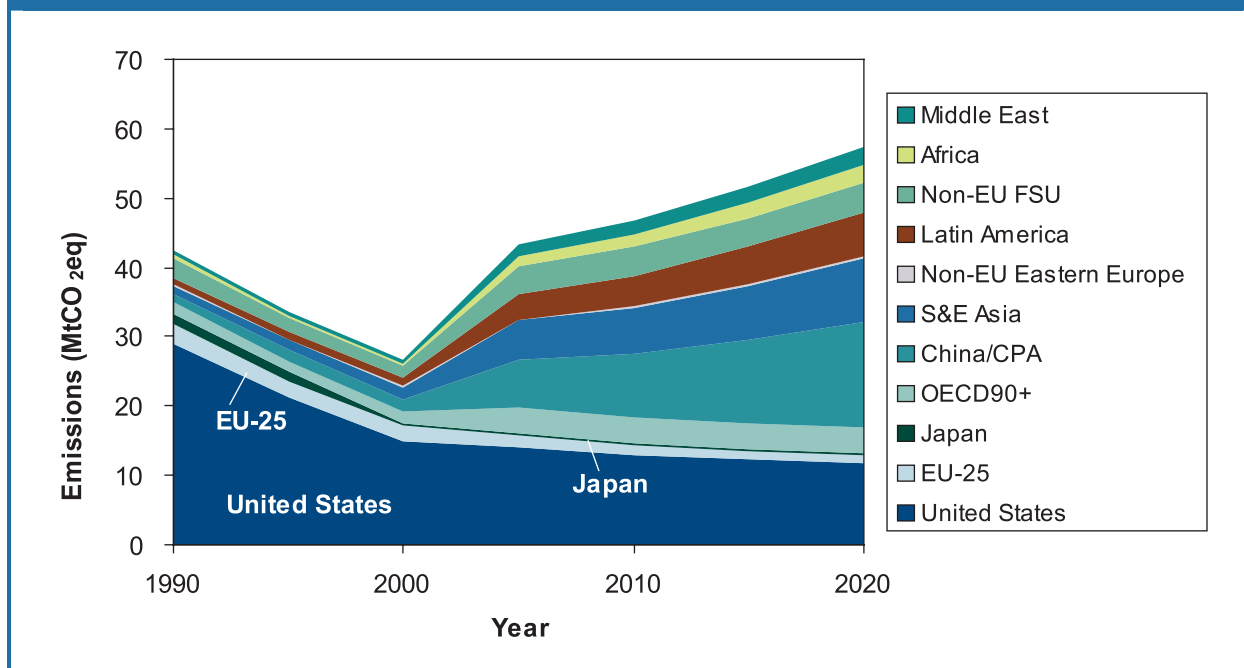
Table 10-2: Total SF₆ Emissions from Electric Power Systems (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2000	2010	2020
Africa	0.5	1.8	2.5
Annex I	20.5	21.8	20.3
Australia/New Zealand	0.3	0.8	0.8
Brazil	0.5	1.6	2.4
China	1.8	9.0	14.9
Eastern Europe	0.4	0.7	0.7
EU-15	1.9	1.4	0.9
India	0.7	2.4	3.5
Japan	0.5	0.3	0.3
Mexico	0.3	1.0	1.6
Non-OECD Annex I	1.5	3.9	3.9
OECD	19.5	20.3	19.8
Russian Federation	1.1	2.9	2.9
South & SE Asia	0.6	2.4	3.2
United States	15.0	12.8	11.8
World Total	26.8	46.8	57.5

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

These global trends are reflected in the trends of the individual regions except for the United States; EU-25; Norway, Switzerland, and Iceland (EU-25+3); and Japan. For the United States, emissions estimates for 1990 through 2003 are taken from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003* (USEPA, 2005). For EU-25+3, emissions estimates for 1990 through 2020 were obtained from *Reductions of SF₆ Emissions from High and Medium Voltage Electrical Equipment in Europe* (Ecofys, 2005). For Japan, emissions estimates for 1990 through 2010 were obtained from *Recent Practice for Huge Reduction of SF₆ Gas Emissions from GIS&GCB in Japan* (Yokota et al., 2005), as well as personal communications with T. Yokota (2006). These studies show declining emissions in these regions through 2003.

As illustrated in Figure 10-1, beyond 2005, emissions in developed countries are expected either to remain steady or to decline. Emissions in non-EU Eastern Europe and non-EU FSU are expected to remain relatively constant through 2020. Because the electric grids in these countries are mature and well developed, it is assumed that there will be no additional growth of emissions from their electric transmission and distribution systems. Any system growth is expected to be offset by decreases in the equipment's average SF₆ capacity and emissions rate as new, small, leak-tight equipment gradually

Figure 10-1: SF₆ Emissions from Electric Power Systems on a Technology-Adoption Scenario—1990–2020 (MtCO₂eq)

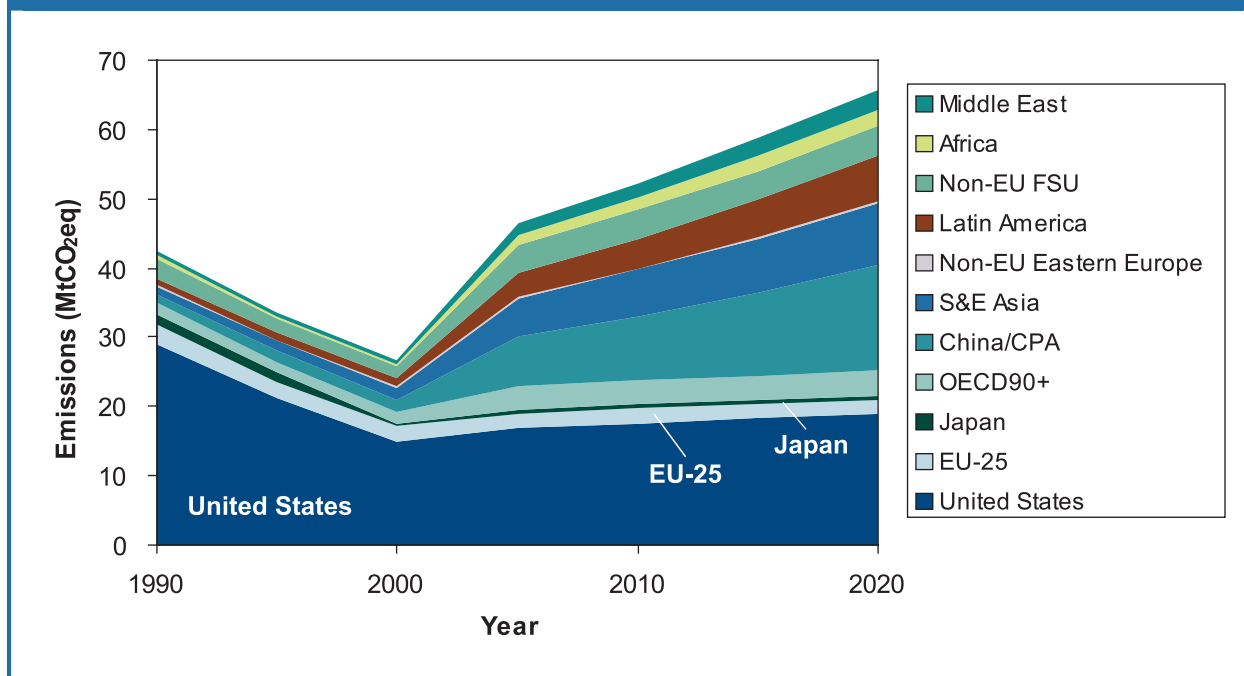
CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = The Organisation for Economic Co-operation and Development.

replace old, large, leaky equipment. In the United States, EU-25+3, and Japan, emissions are expected to continue to decline as utilities, through government-sponsored voluntary and mandatory programs, implement reduction measures such as leak detection and repair and gas recycling practices.

In contrast, emissions from developing regions (i.e., Latin America, South and East Asia, Middle East, Africa and China/CPA) are expected to continue growing during the next 15 years. In these regions, it is assumed that SF₆-containing equipment has been installed relatively recently and that all equipment is new. Consequently, as infrastructure expands to meet the demands of growing populations and economies, emissions are estimated to grow at a rate proportional to country- or region-specific net electricity consumption (USEIA, 2002). This growth drives global emissions growth, resulting in worldwide emissions of 57 MtCO₂eq in 2020. By 2020, Latin America, South and East Asia, the Middle East, Africa, and China/CPA are expected to account for 63 percent of total emissions, versus approximately 10 percent in 1990. OECD is projected to account for only 29 percent of global emissions in 2020, versus approximately 82 percent in 1990.

IV.10.1.2 No-Action Baseline

As illustrated in Figure 10-2, baseline emissions for the period 1990 through 2000 follow the same trajectory as those under the technology-adoption scenario, with both baselines diverging after 2003. Assumptions and emissions estimates for developing regions (i.e., Latin America, South, and East Asia, Middle East, Africa and China/CPA) are the same as discussed under the technology-adoption baseline. For the United States, Japan, EU-25, and EU-25+3, it is assumed that no additional voluntary measures are adopted after 2003. For the United States, EU-25+3, and Japan, emissions are expected to increase from 2003 levels, with system growth being the driver in the EU and Japan. The marked increase in U.S.

Figure 10-2: SF₆ Emissions from Electric Power Systems on a No-Action Scenario—1990–2020 (MtCO₂eq)

CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; S&E Asia = Southeast Asia; OECD90+ = The Organisation for Economic Co-operation and Development.

emissions after 2000 is an artifact of the method used to estimate U.S. emissions in the no-action scenario. Under this approach, the U.S. emissions factor was assumed to revert to its relatively high 1999 level in 2005, despite reductions in earlier years.

The assumption that the United States, EU-25+3, and Japan will pursue no additional voluntary measures after 2003 increases their contribution to world emissions in 2020. Unlike the technology-adoption baseline, where OECD accounts for only 29 percent of emissions in 2020, in the no-action baseline, OECD accounts for 38 percent. In contrast, the contribution of developing regions, such as Latin America, South and East Asia, the Middle East, Africa, and China/CPA decreases to 55 percent of total 2020 emissions in the no-action scenario, versus 63 percent under the technology-adoption scenario.

IV.10.2 Cost of SF₆ Emissions Reduction from Electric Power Systems

IV.10.2.1 Abatement Options

SF₆ emissions during use of electrical equipment can occur either during the maintenance and disposal of equipment or during the operation of equipment because of the failure of mechanical seals or breaks in gas-insulated equipment enclosures.

For all countries except the EU-25, EU-25+3, and Japan, this analysis models three potential abatement options for reducing SF₆ emissions from electric power systems:

- SF₆ recycling,
- leak detection and repair (LDAR), and

- equipment refurbishment.

For the EU-25+3 and Japan, this analysis models the abatement options identified in Ecofys (2005), because the baseline emissions for Europe (in both the no-action and technology-adoption scenarios) are based on data presented in Ecofys (2005). Using the Ecofys options therefore maintains consistency with the assumptions used in that report to estimate current and future emissions (i.e., current and future levels of implementation of reduction options). These options are applied to Japan, because Japan is believed to have implemented reduction options to approximately the same extent as Europe. The following options are identified in Ecofys:

- awareness, including training, monitoring, and labeling;
- evacuation of equipment;
- repair or replacement; and
- decommissioning infrastructure.

Although Ecofys (2005) identifies four options, they are, for the most part, similar in nature to those analyzed for countries other than the EU-25+3 and Japan in this study. For example, evacuation of equipment is similar to the SF₆ recycling option in that both address the recovery of SF₆ from closed pressure equipment. Decommissioning infrastructure also includes recovery of gas, in this case from retiring equipment. Repair and replacement includes activities similar to those included in both the LDAR and refurbishment options. As for awareness, some of the associated training costs and emissions reductions are accounted for within the SF₆ recycling option. The remainder of Section IV.10.3 provides an overview of each abatement option and details the associated emissions and cost assumptions.

Abatement Options—For All Countries Except EU-25+3 and Japan

Emissions Available for Abatement

For most of the other sectors in this analysis, the quantity of emissions that can be abated through the applicable abatement options is estimated directly based on the activity level and the fraction of the emitting activity that remains uncontrolled in the baseline. For this sector, however, the analysis begins with an emissions estimate rather than an activity level, making the estimate of uncontrolled emissions somewhat more complicated. To develop the estimate of currently uncontrolled emissions, the technical applicability, current market penetration, and reduction efficiency of the three abatement options are estimated and applied to the hypothetical emissions that would result if emissions were not controlled at all. Using this approach, it is possible to estimate the fraction of current emissions that consist of residual emissions from the options as they are implemented in the baseline, as well as the fractions of current emissions that can still be abated by the three options. For equipment whose emissions are not controlled, 33 percent of emissions are estimated to occur during operation as a result of leaks, and 67 percent are estimated to occur during maintenance and disposal as a result of failure to recycle. This apportionment is inferred from O'Connell et al. (2002), who report that leakage losses account for between 0.5 percent and 1 percent per year, and handling losses account for between 1 percent and 2 percent per year. Based on discussions with electric utilities and manufacturers of SF₆ recycling equipment, this analysis assumes that recycling, LDAR, and refurbishment options are currently applied to 80 percent of electrical equipment. In addition, the analysis assumes that those utilities that currently recycle SF₆ recover 80 percent of the gas each time. That is, 80 percent of the gas enclosed in electrical equipment is assumed to be removed as the enclosure pressure drops from operational conditions to zero pounds per square inch (psig). The abatement option described below assumes that, in the presence of a carbon price, an additional 15 percent of the SF₆ will be recovered—95 percent overall—which requires pulling a vacuum on the equipment. This is within the technical capability of the equipment but is relatively time consuming. Together, all of these assumptions lead to the conclusion that 49 percent of the baseline

emissions remain available to abatement through recycling, 7 percent remains available to abatement through LDAR, and 1 percent remains available to abatement through refurbishment.

SF₆ Recycling

For equipment whose emissions are not controlled, 67 percent of emissions are estimated to occur during equipment servicing and disposal. This estimate is based on information reported by the International Council on Large Electric Systems (CIGRE) (O'Connell et al., 2002), which indicates that leakage and handling losses are on the order of between 0.5 percent and 1 percent per year and 1 percent to 2 percent per year, respectively. Recycling gas cart systems typically withdraw, purify, and return the SF₆ gas to the gas-insulated equipment. Recycling equipment vendors state that utilities that use the equipment typically recover about 80 percent of the gas held in high-voltage equipment, although recycling equipment is theoretically capable of capturing almost 100 percent. Typically, utilities end recovery early because the current price of the SF₆ does not justify spending the additional time required to recover it fully. In other words, it would take as much time to recover the final 20 percent of the gas as it takes to recover the first 80 percent (by mass), because the density of the gas declines during the recovery process. Consequently, it is assumed that 80 percent recovery is the current standard industry practice.

The use of recycling equipment is considered a relatively straightforward option for conservative gas-handling practices, and gas cart ownership and use have increased significantly worldwide (O'Connell et al., 2002; Ellerton, 1997). Communications with gas cart manufacturers have also indicated that the majority of electric utilities in North and South America use recycling equipment (ICF, 2001). This analysis assumes that the current and future market penetration of recycling equipment in the baseline is 80 percent in both developed and developing countries.

In the presence of a carbon price, this analysis assumes that utilities that currently recover SF₆ will recover it more deeply, recovering 95 percent of the gas rather than the current 80 percent, and the analysis assumes that the 20 percent of utilities that do not currently recover SF₆ will begin recovering it to the 95 percent level. Based on these assumptions, approximately 39 percent of the emissions reductions for recycling are achieved through deeper recovery (going from 80 percent to 95 percent), while 61 percent of these reductions are achieved by increasing the market share of recycling.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** The capital cost for smaller-capacity recycling equipment is between \$5,000 and \$50,000 per unit and for higher-capacity units between \$50,000 and \$130,000 per unit (ICF, 2001). Because older, larger electrical equipment is being replaced with newer, smaller volume electrical equipment in developed countries, and because developing countries, which have newer electrical T&D networks, use smaller electrical equipment, an average cost of \$25,500 per unit was assumed. Total country-specific capital costs were calculated by estimating the number of recycling gas cart units required to ensure 100 percent market penetration. In the United States, it is estimated that between 750 and 1,000 recycling gas carts are in use, based on communications with gas cart manufacturers (ICF, 2001). Based on the assumption that this number represents an 80 percent market penetration, the number of recycling units required to establish a 100 percent U.S. market penetration was estimated to be between 190 and 250 units. For other countries, the number of recycling units that can still be implemented, based on an existing 80 percent market penetration scenario, was estimated as the product of the number of recycling units required to achieve 100 percent market penetration in the United States and the ratio of country-specific net electricity consumption to U.S. net electricity consumption (USEIA, 2002).

- Annual Costs.** Equipment recycling rates range from 50 to 500 pounds SF₆ per hour (Dilo, 2003; Cryoquip, 2003). Actual recovery speeds depend on recovery pump equipment, operating pressure, and connecting equipment. As a conservative estimate, and considering that most SF₆ users will require smaller-grade equipment because of smaller charge sizes, the average recovery rate for removing gas held under positive pressure (i.e., 80 percent by mass) is assumed to be 100 pounds SF₆ per hour. However, once a vacuum is drawn, the average recovery rate falls below this level. Based on the assumption that 100 pounds per hour represents the average recovery rate for recovering the first 80 percent of gas (achieving zero psig), average recovery rates were calculated for recovery of the gas from its initial pressure to a vacuum (95 percent recovery), which is applicable to the utilities that are not currently conducting recycling (i.e., 20 percent of the market) and recovery of the gas from zero psig to a vacuum (15 percent), which is applicable to the 80 percent of the market that currently only achieves 80 percent recovery. These average recovery rates were 64 and 22 pounds per hour, respectively. The marginal labor time required for recycling the gas is equal to the total gas recycled in the country multiplied by the estimated emissions that can be reduced by increasing the market penetration of recycling (61 percent) and increasing the depth of recovery from 80 percent to 95 percent (39 percent), and dividing by the corresponding average recycling rate (64 and 22 pounds per hour, respectively). Associated labor costs were estimated for a two-person crew and assumed an hourly labor rate of \$50 per hour. To account for additional labor time spent for training and setting up/tearing down recycling equipment, conservative multipliers of 1.02 (i.e., assuming 2 percent [1 week] of annual labor time spent conducting training) and 1.5 were also applied.
- Cost Savings.** It is assumed that all SF₆ recycled is a cost savings, because the facility's SF₆ purchase and consumption rate will decrease. For this analysis, it is assumed that the cost of SF₆ is \$7 per pound.

Leak Detection and Repair

LDAR abatement options aim to identify and reduce the SF₆ leakage that occurs from gas-insulated equipment. For equipment whose emissions are not controlled, 33 percent of emissions are estimated to occur during equipment operation, with 30 percent controllable through LDAR. SF₆ leak detection is accomplished through various techniques, including "sniffing" for gas with SF₆ gas sensors and using laser-based remote sensing technology (McRae, 2000). Similar to SF₆ recycling, the current market penetration of this option is assumed to be 80 percent of SF₆ use. LDAR measures are assumed to have a reduction efficiency of 50 percent.

Cost and Emissions Reduction Analysis

- Capital/Upfront Costs.** Leak detection equipment costs vary depending on the type of instrument used. For simple screening devices, costs are believed to be minimal (i.e., less than \$2,000 per unit). For expensive items, such as the laser-based imaging system, it is assumed that facilities will lease equipment or contract private companies to provide leak detection services. Hence, LDAR mitigation options will have no capital costs.
- Annual Costs.** It is assumed that the average leak size is 25 pounds SF₆ per leak per year and that the average time to detect and repair a leak is 2 and 8 hours, respectively (ICF, 2000). The marginal labor time required for LDAR is equal to the total gas emitted from this source divided by the average leak size and multiplied by the average time to detect and service a leak. Associated labor costs assume LDAR requires a one-person and two-person crew, respectively, and that the hourly labor rate is \$50 per hour.

- **Cost Savings.** It is assumed that all SF₆ saved during leak detection and maintenance activities represents a cost savings, because the facility SF₆ purchase and consumption rate will decrease. For this analysis, it is assumed that the cost of SF₆ is \$7 per pound.

Equipment Refurbishment

Unlike LDAR-based repairs, which tend to focus on small leaks on specific components, such as a bushing flange gasket, refurbishment addresses the need, when leakage losses are large, for a comprehensive repair. Refurbishment is a process in which equipment is disassembled and rebuilt (and possibly upgraded) using remachined, cleaned, and/or new components. Generally, equipment refurbishment represents the cheaper of two possible options: 1) equipment replacement, which for a large breaker (362 kV) can be on the order of \$300,000 to \$400,000; and 2) refurbishment, which may cost around \$100,000 (McCracken et al., 2000).

It is assumed that 33 percent of uncontrolled emissions occur during equipment operation; of this total, 3 percent is assumed to be controllable through refurbishment. Similar to the other options, refurbishment is assumed to have a current market penetration of 80 percent. Refurbishment measures are assumed to have a reduction efficiency of 95 percent.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** The cost of labor and parts to undertake the refurbishment of a circuit breaker with a nameplate capacity of 1,500 pounds and a leak rate of 20 percent is assumed to be approximately \$100,000 (McCracken et al., 2000). This includes equipment disassembly, rebuild, testing, and installation.
- **Annual Costs.** During refurbishment, equipment is completely remanufactured. As a result, this option is considered a one-time activity, with no annual costs for the lifetime of the project period (i.e., 15 years).
- **Cost Savings.** It is assumed that all SF₆ saved during refurbishment activities represents a cost savings, because the facility SF₆ purchase and consumption rate will decrease. For this analysis, it is assumed that the cost of SF₆ is \$7 per pound.

Abatement Options—EU-25+3 and Japan Only

For each of the following options, cost and emissions reduction potential assumptions are detailed in Ecofys (2005). Although these options were developed for EU-25+3 countries, they have also been applied to Japan, because Japanese equipment designs and maintenance practices are believed to be similar to those in the EU-25+3 (Ecofys, 2005; Yokota et al., 2005).

- **Awareness, Including Training, Monitoring, and Labeling.** Awareness includes costs to implement training programs for SF₆ gas handling during equipment top-up and maintenance. Awareness also includes costs to implement SF₆ gas management systems, where SF₆ inventories, purchases, and gas use are monitored.
- **Evacuation of Equipment.** Evacuation includes costs associated with attaining a higher level of SF₆ recovery from closed-pressure equipment (i.e., drawing evacuation pressure from 50 millibar [mbar] down to 20 mbar).
- **Repair or Replacement.** Ecofys (2005) assumes that 3 percent of closed-pressure systems leak more than 2.5 percent per year greater than their design leak rates. Costs are based on 90 percent of equipment being repaired, with the remainder replaced.
- **Decommissioning Infrastructure.** This includes costs to develop infrastructure to handle end-of-life treatment (both gas and equipment material) of SF₆ electrical equipment.

IV.10.3 Results

This section discusses the results from the MAC analysis for the world and several regions, for both the no-action and technology-adoption scenarios.

IV.10.3.1 Data Tables and Graphs

Based on the trends described above, the USEPA developed MACs for several regions. Tables 10-3 through 10-8 provide a summary of the potential emissions reduction opportunities and associated costs for these regions in 2010 and 2020 for the no-action and technology-adoption baselines. The costs to reduce 1 tCO₂eq are presented for a discount rate of 10 percent and a tax rate of 40 percent.

Table 10-3: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Electric Power Systems at a 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.00	1.03	1.03	1.03	1.03	1.03
Annex I	12.23	14.99	15.00	15.00	15.04	15.04
Australia/New Zealand	0.41	0.48	0.48	0.48	0.48	0.48
Brazil	0.79	0.93	0.93	0.93	0.93	0.93
China	4.99	5.13	5.13	5.13	5.13	5.13
Eastern Europe	0.29	0.41	0.41	0.41	0.41	0.41
EU-15	0.00	0.66	0.67	0.67	0.70	0.70
India	1.34	1.38	1.38	1.38	1.38	1.38
Japan	0.00	0.15	0.15	0.15	0.16	0.16
Mexico	0.49	0.57	0.57	0.57	0.57	0.57
Non-OECD Annex I	2.15	2.22	2.22	2.22	2.22	2.22
OECD	11.25	14.14	14.15	14.15	14.19	14.19
Russian Federation	1.60	1.64	1.64	1.64	1.64	1.64
South & SE Asia	1.22	1.37	1.37	1.37	1.37	1.37
United States	8.57	10.05	10.05	10.05	10.05	10.05
World Total	25.53	29.24	29.26	29.26	29.30	29.30

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Table 10-4: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.40	1.45	1.45	1.45	1.45	1.45
Annex I	12.85	16.11	16.12	16.12	16.16	16.16
Australia/New Zealand	0.41	0.48	0.48	0.48	0.48	0.48
Brazil	1.18	1.38	1.38	1.38	1.38	1.38
China	8.29	8.52	8.52	8.52	8.52	8.52
Eastern Europe	0.29	0.45	0.45	0.45	0.46	0.46
EU-15	0.00	0.95	0.95	0.95	0.98	0.98
India	1.92	1.97	1.97	1.97	1.97	1.97
Japan	0.00	0.21	0.21	0.21	0.22	0.22
Mexico	0.76	0.89	0.89	0.89	0.89	0.89
Non-OECD Annex I	2.15	2.22	2.22	2.22	2.22	2.22
OECD	12.33	15.80	15.80	15.80	15.84	15.84
Russian Federation	1.60	1.64	1.64	1.64	1.64	1.64
South & SE Asia	1.63	1.82	1.82	1.82	1.82	1.82
United States	9.18	10.78	10.78	10.78	10.78	10.78
World Total	32.69	37.32	37.33	37.33	37.36	37.36

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Table 10-5: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.00	1.03	1.03	1.03	1.03	1.03
Annex I	8.15	9.24	9.24	9.24	9.24	9.24
Australia/New Zealand	0.41	0.48	0.48	0.48	0.48	0.48
Brazil	0.79	0.93	0.93	0.93	0.93	0.93
China	4.99	5.13	5.13	5.13	5.13	5.13
Eastern Europe	0.29	0.30	0.30	0.30	0.30	0.30
EU-15	0.00	0.00	0.00	0.00	0.00	0.00
India	1.34	1.38	1.38	1.38	1.38	1.38
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.49	0.57	0.57	0.57	0.57	0.57
Non-OECD Annex I	2.15	2.20	2.20	2.20	2.20	2.20
OECD	7.17	8.41	8.41	8.41	8.41	8.41
Russian Federation	1.60	1.64	1.64	1.64	1.64	1.64
South & SE Asia	1.22	1.37	1.37	1.37	1.37	1.37
United States	4.48	5.25	5.25	5.25	5.25	5.25
World Total	21.44	23.50	23.50	23.50	23.50	23.50

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Table 10-6: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Electric Power Systems at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	1.40	1.45	1.45	1.45	1.45	1.45
Annex I	3.67	7.68	7.68	7.68	7.68	7.68
Australia/New Zealand	0.41	0.48	0.48	0.48	0.48	0.48
Brazil	1.18	1.38	1.38	1.38	1.38	1.38
China	8.29	8.52	8.52	8.52	8.52	8.52
Eastern Europe	0.29	0.30	0.30	0.30	0.30	0.30
EU-15	0.00	0.00	0.00	0.00	0.00	0.00
India	1.92	1.97	1.97	1.97	1.97	1.97
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.76	0.89	0.89	0.89	0.89	0.89
Non-OECD Annex I	2.15	2.20	2.20	2.20	2.20	2.20
OECD	3.15	7.38	7.38	7.38	7.38	7.38
Russian Federation	1.60	1.64	1.64	1.64	1.64	1.64
South & SE Asia	1.63	1.82	1.82	1.82	1.82	1.82
United States	0.00	3.69	3.69	3.69	3.69	3.69
World Total	23.51	28.88	28.88	28.88	28.88	28.88

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Table 10-7: Emissions Reduction and Costs in 2020—No-Action Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Recycling	−\$0.61	−\$0.09	30.65	46.6%	30.65	46.6%
Decommissioning	\$1.47	\$1.47	1.04	1.6%	31.69	48.2%
Awareness/training	\$2.04	\$2.04	0.32	0.5%	32.01	48.7%
Leak detection	−\$0.56	\$2.68	4.38	6.7%	36.39	55.3%
Refurbishment	\$5.01	\$5.01	0.93	1.4%	37.32	56.7%
Evacuation	\$27.28	\$27.28	0.01	0.0%	37.33	56.8%
Repair and replacement	\$45.51	\$45.51	0.04	0.1%	37.36	56.8%

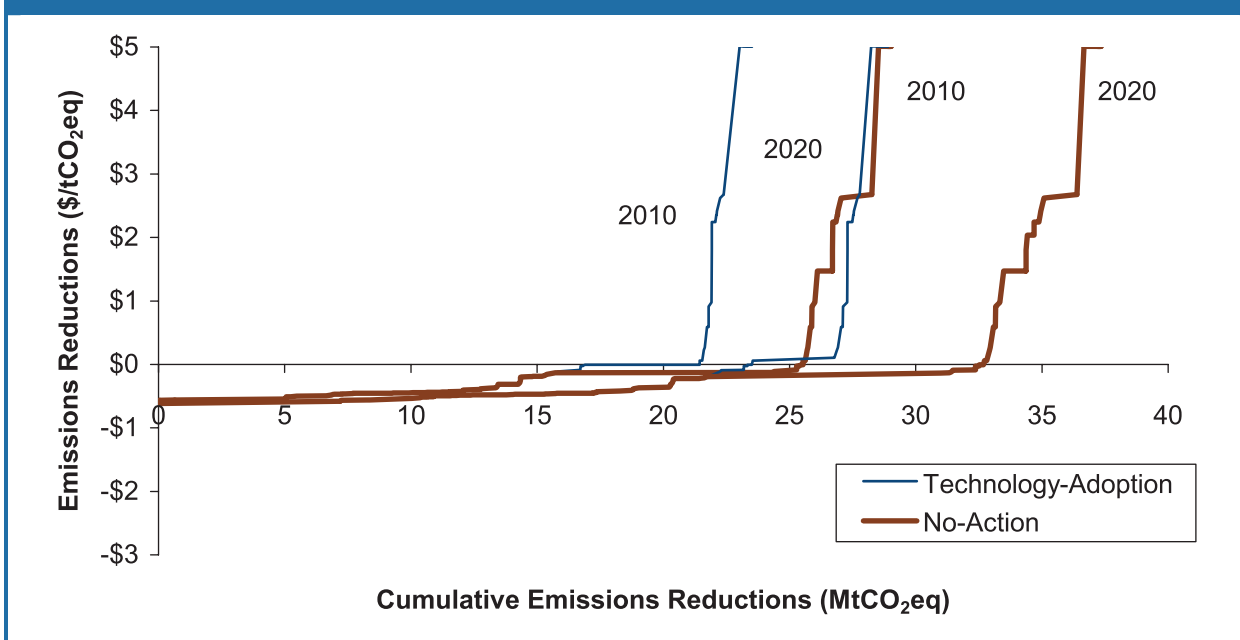
Table 10-8: Emissions Reduction and Costs in 2020—Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
Recycling	−\$0.61	\$0.10	24.61	42.8%	24.61	42.8%
Decommissioning	\$1.47	\$1.47	0.00	0.0%	24.61	42.8%
Awareness/training	\$2.04	\$2.04	0.00	0.0%	24.61	42.8%
Leak detection	−\$0.56	\$2.68	3.17	5.5%	27.78	48.3%
Refurbishment	\$5.01	\$5.01	1.10	1.9%	28.88	50.2%
Evacuation	\$27.28	\$27.28	0.00	0.0%	28.88	50.2%
Repair and replacement	\$45.51	\$45.51	0.00	0.0%	28.88	50.2%

IV.10.3.2 Global and Regional MACs and Analysis

This section discusses the results from the MAC analysis of the world and selected countries and regions, including China, Japan, the United States, the EU-15, other OECD, and the rest of the world.

Figure 10-3 presents the 2010 and 2020 global technology-adoption and no-action MACs for electric power systems. For the no-action MACs, significant reductions (comprising more than 48 percent of the baseline emissions from this sector) are achievable below \$0/tCO₂eq in 2010 and 2020. These reductions occur through the implementation of SF₆ recycling and LDAR options in most countries, except EU-25+3 and Japan. For the latter countries, decommissioning and awareness/training reduce approximately 2 percent of global baseline emissions, with both options being implemented below \$2/tCO₂eq.

Figure 10-3: 2010 and 2020 Global Technology-Adoption and No-Action MACs for Electric Power Systems

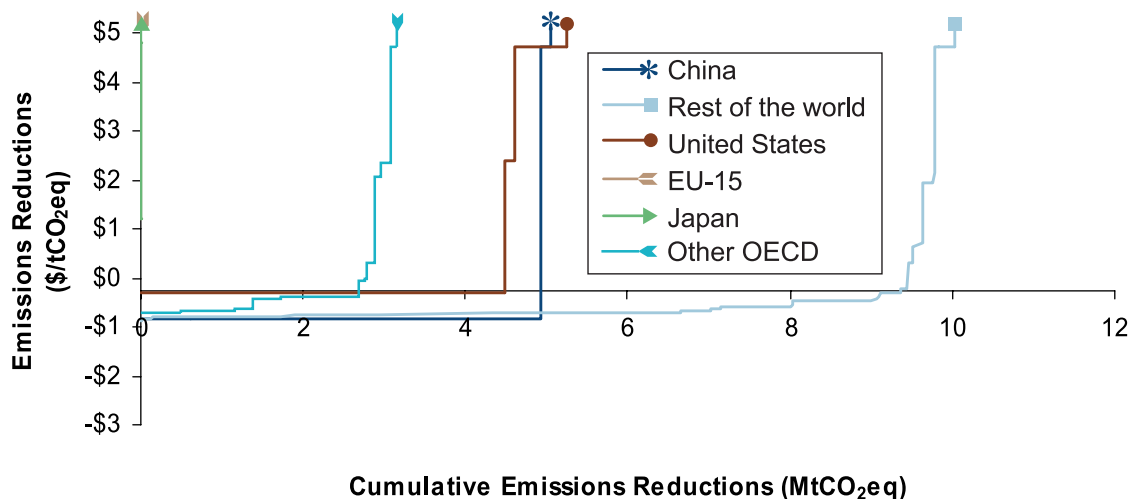
In the technology-adoption MACs, no reductions are available in EU-25+3 and Japan in 2010 and 2020, because mitigation technologies are assumed to be fully implemented in the baselines of these countries. For the remaining countries, more than 40 percent of baseline emissions can be reduced for less than \$0/tCO₂eq through SF₆ recycling and LDAR measures. An additional 10 percent of baseline emissions can be reduced through \$5/tCO₂eq. Most of these reductions result from SF₆ recycling and LDAR in developed regions, such as the United States, and the implementation of refurbishment in all countries. The rightward shift in technology-adoption and no-action MACs between 2010 and 2020 reflects increasing emissions from electric grid infrastructure growth, specifically in developing country regions, such as China, Latin America, and Africa. In developed countries, such as the United States, EU-25+3, and Japan, voluntary and mandatory emissions reduction programs reduce both baseline emissions and the reductions available in the technology-adoption MACs. (As noted above, emissions reductions in the technology-adoption baseline actually exhaust the available reductions in Europe and Japan, leaving no reductions in the technology-adoption MACs for these regions.) In the no-action MACs, however, it is assumed that additional voluntary measures will not be implemented after 2003; consequently, U.S. emissions increase while emissions from the EU-25+3 and Japan remain constant between 2010 and 2020, reflecting the stabilization of European and Japanese SF₆ banks.

Figures 10-4 and 10-5 present 2010 and 2020 technology-adoption MACs for China, Japan, the United States, the EU-15, other OECD, and the rest of the world. These figures show the regional contributions to the global trends described above. As noted above, EU-25+3 and Japan offer no emissions reduction opportunities in 2010 or 2020, because it is assumed that all mitigation measures, such as awareness/training, decommissioning, evacuation, and repair and replacement, are implemented in their baselines. For all other countries, SF₆ recycling offers the opportunity for significant emissions reductions at low carbon cost (i.e., less than or equal to \$0.10/tCO₂eq). LDAR offers reductions at somewhat higher costs ranging from about -\$0.56/tCO₂eq to \$2.68/tCO₂eq. LDAR costs have a large labor component compared with the recycling option. Consequently, abatement costs are higher in countries where labor costs are high, such as the United States, Australia, and Canada, but are very low in other regions, such as China, Latin America, and Africa. The pronounced “elbows” in the curves for most regions are indicative of the lower emissions reduction potential and higher abatement costs offered by LDAR and refurbishment, compared with recycling.

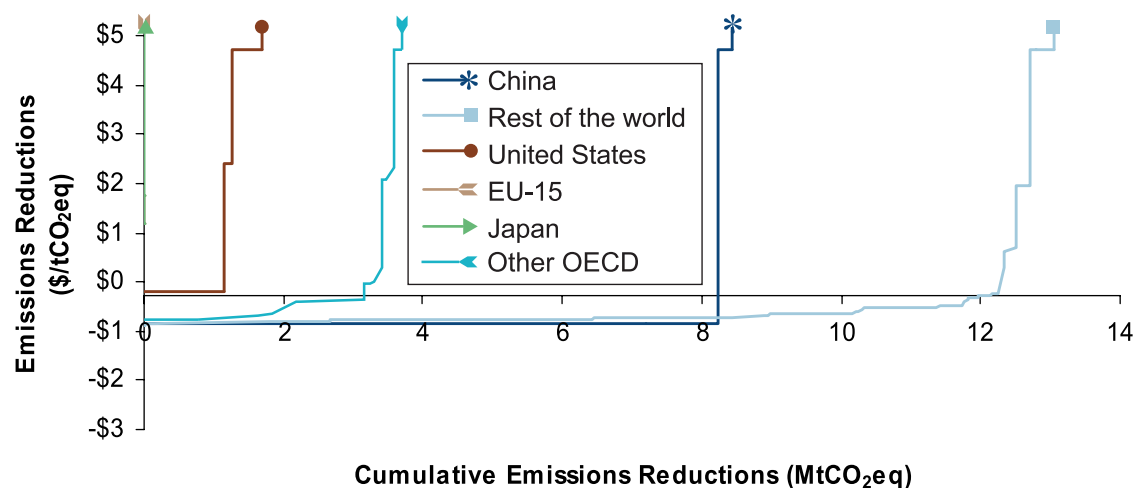
In 2020, the MACs for all countries and regions have a similar profile to 2010, where SF₆ recycling is followed by LDAR and refurbishment. However, for some countries and regions, there are minor shifts in the curves, specifically those for developing economies, such as China, other OECD, and the rest of the world. This shift reflects the potential for increased emissions reductions as electric transmission and distribution grids expand and associated SF₆ emissions increase to accommodate growing commercial and residential energy needs. In comparison, for the United States, the 2020 MAC shifts left as emissions available for abatement decrease because of the continuing success of domestic voluntary programs.

IV.10.3.3 Uncertainties and Limitations

In developing these estimates of emissions, reductions, and costs, the USEPA made use of multiple international data sets and IPCC guidance on estimating emissions from this source. Nevertheless, this analysis is subject to a number of uncertainties that affect both global and country-specific estimates of emissions, reductions, and costs, particularly estimates for regions other than the United States, Japan, and the EU-25+3.

Figure 10-4: 2010 Regional Technology-Adoption MACs for Electric Power Systems

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

Figure 10-5: 2020 Regional Technology-Adoption MACs for Electric Power Systems

EU-15 = European Union; OECD = The Organisation for Economic Co-operation and Development.

SF₆ Emissions from Electric Power Systems

Although emissions from the United States, EU-25+3, and Japan are based on bottom-up evaluations of emissions rates and SF₆ banks in equipment, remaining country-specific estimates are based on apportioning RAND survey data (Smythe, 2004) using net electricity consumption statistics. The relationship between emissions and electricity consumption varies between regions and over time, particularly as countries begin to adopt emission-reducing practices and technologies. Additional uncertainties associated with this approach are described in detail in the USEPA (2006) report *Global Anthropogenic Non-CO₂ Greenhouse Gas Emissions: 1990–2020*. These uncertainties affect both the global total and the country-by-country apportionment of that total.

Emissions Apportionment/Market Penetration/Reduction Efficiency for All Regions, Except EU-25+3 and Japan

- This analysis is based on the assumption that 67 percent of emissions are attributable to the failure to recycle during maintenance and disposal, while 33 percent of emissions are due to equipment leakage. The basis for this assumption is a study performed by CIGRE and reported by O’Connell et al. (2002). There is very limited information on the apportionment of emissions between handling and leakage losses; consequently, this is a potential source of uncertainty.
- This analysis assumes emissions are due to leakage and failure to recycle only; however, losses due to improper handling of SF₆ gas may also contribute to baseline emissions. Because of limited information, this potential emissions source is not fully addressed in this analysis.
- Estimates of current market penetration are based on communications with U.S.-based industry experts. These estimates are assumed to apply to all global regions; however, it is possible that the current 80 percent penetration estimate may be too high for some regions, especially developing countries. For example, it is possible that developing countries may not have the resources to implement recycling and LDAR to the levels assumed in this analysis. If market penetration is lower than assumed, the potential for emissions reduction from these countries will be higher.
- For LDAR, reduction efficiency is assumed to be 50 percent; this is an average number that accounts for varying degrees of LDAR success. However, it is technically possible, with current practices (e.g., laser leak detection and new sealant technology) to achieve reductions that are closer to 100 percent.
- For refurbishment, reduction efficiency is assumed to be 95 percent. As with LDAR, it is technically feasible to achieve reductions of 100 percent; however, the current estimate assumes varying degrees of refurbishment success.

Emissions Apportionment/Market Penetration/Reduction Efficiency for EU-25+3 and Japan Only

This analysis uses cost and emissions reduction potentials developed for EU-25+3 countries (Ecofys, 2005). The same costs and emissions reduction potentials have been applied to Japan on the assumption that Japan and Europe have similar electric transmission and distribution infrastructures and maintenance practices. Because there are likely to be some differences in the general age and type of equipment used, as well as in the current level of implementation of abatement options, this assumption is a potential source for uncertainty in the MACs. Additional uncertainties associated with the specific options used for EU-25+3 and Japan are detailed in Ecofys (2005).

Estimation of Annual Cost

- For recycling and LDAR, marginal labor cost estimates depend on average recycling rates (64 and 22 pounds per hour) and the average size of a leak (25 pounds per year per leak), respectively. Both of these estimates may vary significantly and are, consequently, a source of uncertainty in the MACs. In developing recycling costs, it is assumed that 61 percent of emissions are abatable through increased market penetration, while 31 percent are abatable through “deeper” recovery (i.e., 80 percent to 95 percent). The apportionment of reductions to these two types of recovery is important because it affects the average recovery rate, and therefore labor costs, assumed in the analysis. However, this apportionment depends on the market penetration, reduction efficiency, and theoretical applicability assumed for recycling, all of which are subject to uncertainty.

- For refurbishment, costs are based on a circuit breaker with a nameplate capacity of 1,500 pounds and an emissions rate of 20 percent; however, depending on the equipment (location, age, and type), these values may vary significantly, adding a source of uncertainty in the MACs.
- Data on leak rates are limited, but a recent USEPA study looking at new equipment leak rates may shed some light on this emissions source.
- Adjusting Costs for Specific Domestic Situations: The annual and capital costs associated with implementing recycling and LDAR options are based on U.S. information. Although adjustments for annual costs are included to account for differing country-specific labor costs, there remains a potential source of uncertainty associated with recycling capital costs. Specifically, other countries may be faced with higher costs from transportation and tariffs associated with purchasing the technology abroad, or they may be faced with lower costs from domestic production of these technologies. Also, it is assumed that LDAR capital costs are minimal; however, repair costs can range from \$10 to \$100,000. Consequently, current MACs may underestimate the dollars per tCO₂e associated with LDAR.

Country-Specific Tax and Discount Rates

A single tax rate is applied to the electric power sector in all countries to calculate the annual benefits of each technology. Tax rates can vary across countries and, in the case of developing countries, taxes may be less applicable. Similarly, the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately calculate benefits and hence breakeven prices.

IV.10.4 References

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IV.11 SF₆ Emissions from Magnesium (Mg) Production

IV.11.1 Source Description

The Mg metal production and casting industry uses SF₆ as a cover gas to prevent the spontaneous combustion of molten Mg in the presence of air. The industry originally adopted SF₆ to replace SO₂ as the primary cover gas. Although recent studies indicate some destruction of SF₆ in its use as a cover gas (Bartos et al., 2003), this analysis follows current IPCC guidelines (IPCC, 2000), which assume that all SF₆ used is emitted into the atmosphere. Fugitive SF₆ emissions may occur in various phases of magnesium manufacture and casting, such as primary production, die-casting, and recycling-based production. Additional processes that may use SF₆ include sand and gravity casting; however, these are assumed to be minor sources and are not included in the analysis. Baseline emissions estimates under both a technology-adoption and a no-action baseline scenario are presented in Tables 11-1 and 11-2.

IV.11.1.1 Technology-Adoption Baseline

Under the Technology-Adoption Baseline scenario, it is assumed that Mg producers and processors outside of China will introduce technologies and practices aimed at reducing SF₆ emissions. Specific technologies include alternative cover gases, such as Novec 612 (a patented fluoroketone produced by 3M) and HFC-134a, and better containment and pollution control systems, which enable the use of SO₂ without the industrial hygiene and odor problems of the past. Under this scenario, International Magnesium Association (IMA) members, who account for 80 percent of the global Mg industry outside of China (IMA, 2003), will meet a target of eliminating the use of SF₆ by 2011.

Figure 11-1 presents total SF₆ emissions from the Mg industry under the technology-adoption scenario from 1990 through 2020. As shown in the graph, total emissions from the Mg industry remained fairly constant through the mid-1990s, but then fell sharply to 9 MtCO₂eq in 2000. The drop in global emissions between 1995 and 2000 is the result of both facility closures in the United States and global reductions in SF₆ usage through more efficient operational practices. The latter is a response to increasing SF₆ gas prices and a growing environmental awareness of its high GWP. Additional plant closings have been reported in Norway, Canada, and Japan, which have added to the decline in the share of global emissions generated by OECD90+ through 2020. This lost production has been primarily absorbed by China, which has dominated the foreign market with low-cost exports.

From 2000 through 2010, the steep decline in global SF₆ emissions is attributable to the adoption of alternative cover-gases; either SO₂ or Novec 612 and HFC-134a. By the end of 2010, in accordance with the IMA goal, all countries except China are assumed to have eliminated the use of SF₆ from Mg production and casting operations.

For China, it is assumed that some primary production and all casting facilities will use SF₆ to produce high-quality magnesium and products for the world market. Because Chinese producers and processors are not IMA members and have not committed to the IMA emissions reduction goal, their SF₆ use is assumed to continue through 2020. Consequently, from 2010 through 2020, the increase in global emissions from 4 to 5 MtCO₂eq will be driven entirely by China, whose emissions are expected to increase from 2 to 4 MtCO₂eq. In 2020, the China/CPA share of global emissions is expected to be 77 percent, compared with 0.3 percent in 1990. OECD's share of global emissions is projected to decrease from 77 percent in 1990 to 21 percent in 2020 because of adoption of the IMA goal and reduction in production capacity. In 2020, U.S. emissions account for a majority of OECD emissions. These emissions are due to some U.S. casting and recycling firms that have not committed to phaseout use of SF₆ (USEPA, 2005).

Table 11-1: Total SF₆ Emissions from Mg Manufacturing (MtCO₂eq)—No-Action Baseline

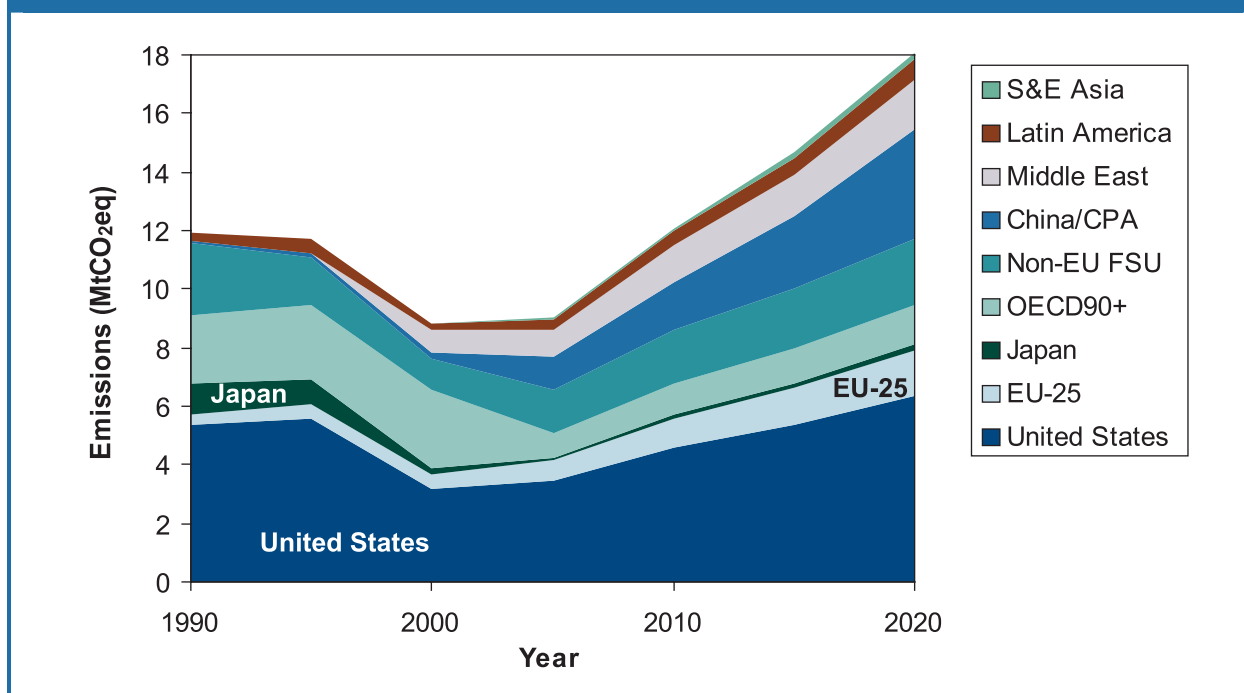
Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	7.4	8.3	11.3
Australia/New Zealand	0.0	0.0	0.0
Brazil	0.2	0.5	0.7
China	0.2	1.7	3.7
Eastern Europe	0.0	0.0	0.0
EU-15	0.5	1.0	1.6
India	0.0	0.0	0.0
Japan	0.2	0.1	0.2
Mexico	0.0	0.0	0.0
Non-OECD Annex I	0.9	1.5	1.8
OECD	6.5	6.8	9.5
Russian Federation	0.9	1.2	1.5
South & SE Asia	0.0	0.0	0.0
United States	3.2	4.6	6.4
World Total	8.8	12.1	18.1

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 11-2: Total SF₆ Emissions from Mg Manufacturing (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2000	2010	2020
Africa	0.0	0.0	0.0
Annex I	7.4	1.7	1.1
Australia/New Zealand	0.0	0.0	0.0
Brazil	0.2	0.1	0.0
China	0.2	1.7	3.7
Eastern Europe	0.0	0.0	0.0
EU-15	0.5	0.1	0.0
India	0.0	0.0	0.0
Japan	0.2	0.0	0.0
Mexico	0.0	0.0	0.0
Non-OECD Annex I	0.9	0.2	0.0
OECD	6.5	1.5	1.0
Russian Federation	0.9	0.1	0.0
South & SE Asia	0.0	0.0	0.0
United States	3.2	1.2	1.0
World Total	8.8	3.6	4.8

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 11-1: SF₆ Emissions from Mg Manufacturing Based on a Technology-Adoption Scenario—1990–2020 (MtCO₂eq)

CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development; S&E Asia = Southeast Asia.

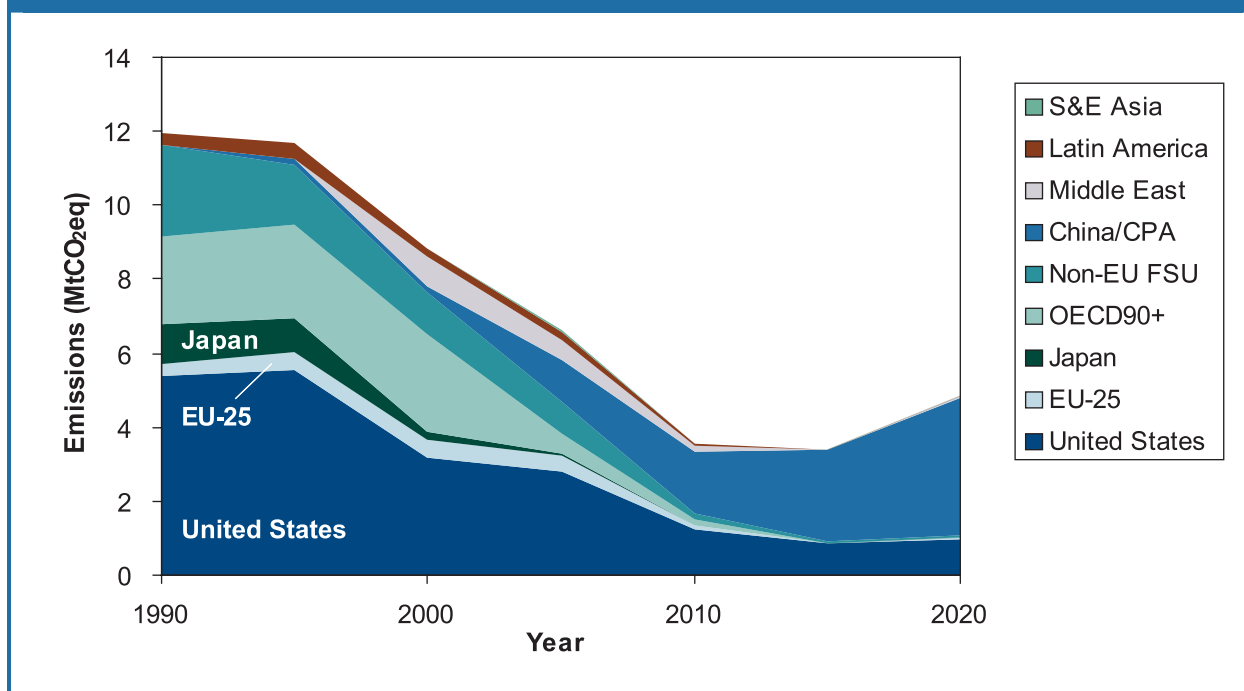
IV.11.1.2 No-Action Baseline

Under the no-action baseline scenario, it is assumed that Mg producers will take no action to reduce their emissions; as a result, emissions projections do not reflect anticipated technology adoptions and/or preventive maintenance steps taken to reduce emissions.

Figure 11-2 presents total SF₆ emissions from Mg production under the no-action scenario from 1990 through 2020. The trends from 1990 through 2000 are the same as those discussed in the technology-adoption baseline. From 2000 through 2020, global emissions in this scenario double to 19 MtCO₂ as the industry experiences strong growth, particularly in the die-casting and recycling segments. China/CPA registers particularly significant emissions growth between 1990 and 2020, increasing its global share of emissions from 0.3 percent in 1990 to approximately 21 percent in 2020. For OECD, emissions in this scenario are assumed to continue to drop between 2000 and 2005 because of facility closures in Canada stemming from pricing pressure from Chinese imports. However, by 2020, OECD emissions are expected to return to 1990 levels as production levels increase. Because global emissions will increase by more than 50 percent during this period, the OECD share of global emissions will fall from 77 percent in 1990 to 53 percent in 2020.

Increasing Chinese primary production and die-casting is being fueled by local and foreign investment, which has driven the overall increase in China/CPA's share of global emissions. This trend in emissions growth is amplified by the assumption that 10 percent of their primary production utilized SF₆ as the cover-gas mechanism.

Figure 11-2: SF₆ Emissions from Mg Manufacturing Based on a No-Action Scenario—1990–2020 (MtCO₂eq)



CPA = Centrally Planned Asia; EU-25 = European Union; Non-EU FSU = non-European Union Former Soviet Union countries; OECD90+ = Organisation for Economic Co-operation and Development; S&E Asia = Southeast Asia.

IV.11.2 Cost of SF₆ Emissions Reduction from Mg Production and Processing Operations

IV.11.2.1 Abatement Options

Two potential abatement options are available for reducing SF₆ emissions from Mg production and processing operations. These technical measures are

- replacement with alternate cover gas—SO₂ and
- replacement with alternate cover gas—fluorinated gases.

The remainder of Section IV.11.2 provides an overview of each abatement option and details the cost and reduction assumptions.

Replacement with Alternate Cover Gas—Sulfur Dioxide

In the past, SO₂ has been used as a cover gas in Mg production and processing activities. However, because of toxicity, odor, and corrosivity concerns, SO₂ use was discontinued in most countries. Current SO₂ technology research aims to improve process feed systems and control technology, as well as to address toxicity and odor issues with improved containment and pollution control systems (Environment Canada, 1998). The use of SO₂ has the potential to reduce SF₆ emissions by 100 percent, because a complete replacement of the cover gas system is involved. It is assumed to be applicable, with limited exceptions (e.g., direct-chill casting), to all global Mg producers and processors. For all countries except China, the maximum market penetration for this option is assumed to be 50 percent of the emissions of

SF₆ in the technology-adoption baseline. For China, where SO₂ replacement is the only option to be implemented, maximum market penetration is assumed to be 100 percent.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** The assumed country-level capital spending requirements for the implementation of an SO₂ system were based on cost information developed for the Canadian Mg production and processing system (Environment Canada, 1998). For Canada, with two primary producers and five casters, the costs to install SO₂ cover gas systems with containment and pollution control systems were estimated at approximately \$10 million. These capital costs were divided by estimated Canadian emissions from Mg production and processing in 2000. The resulting capital cost per tCO₂eq, \$5.73 per tCO₂eq, was then applied to the rest of the world.
- **Annual Costs.** Because of potential employee turnover, it is assumed that costs associated with worker training will occur on an annual basis at a cost of \$50,000 per facility. Assuming seven facilities were operating in Canada in 2000, total annual costs of \$350,000 were divided by estimated Canadian emissions from Mg production and processing in 2000, adjusted to account for the variation of labor rates across countries and applied to the rest of the world.
- **Cost Savings.** The price of SO₂ is significantly lower than that of SF₆. Using industry-based estimates, the installation of SO₂ technology will reduce gas purchase costs by approximately 90 percent (ICF, 1998). It is assumed that all primary producers, casters, and recyclers use similar amounts of SF₆.

Replacement with Alternate Cover Gas—Fluorinated Gases

Research has yielded a number of candidate fluorinated compounds, such as Novec 612 and HFC-134a, as cover gas substitutes for SF₆ (Mibrath, 2002; Rickets, 2002; Hillis, 2002). While fluorinated gases have an advantage over SO₂ because they have potentially fewer associated health, odor, and corrosive impacts, some current candidate gases still have GWPs. However, these GWPs are well below that of SF₆, and within a few years, fluorinated gases will likely provide a functional replacement for SF₆. It is estimated that where this technology is implemented, GWP-weighted cover gas emissions could be reduced by 95 percent to essentially 100 percent. (This analysis uses an average reduction of 97 percent.) This option is assumed to be applicable to all countries that produce and/or process Mg, except China, where only SO₂ replacement is assumed to be implemented. For those countries in which the option is implemented, the maximum market penetration is assumed to be 50 percent of the baseline emissions of SF₆ in the technology-adoption scenario.

Cost and Emissions Reduction Analysis

- **Capital/Upfront Costs.** The capital costs associated with adopting the various fluorinated gases are likely to vary, with some gases requiring relatively little retrofitting of the SF₆ cover gas system and others requiring more. This analysis conservatively assumes that, on average, the capital costs of replacing SF₆ with fluorinated gases will be the same as the capital costs of replacing SF₆ with SO₂, which include costs for developing a special distributed feed system and process and implementing pollution control systems.
- **Annual Costs.** Costs are conservatively assumed to be similar to those required for SO₂ replacement.
- **Cost Savings.** It is assumed that alternate fluorinated gases will cost the same as SF₆; hence, no cost savings will be realized with a switch to this technology.

IV.11.3 Results

This section discusses the result from the MAC analysis for the world and various regions for the no-action and technology-adoption scenarios.

IV.11.3.1 Data Tables and Graphs

Tables 11-3 through 11-8 provide a summary of the potential emissions reduction opportunities and associated costs for the world and various regions in 2010 and 2020 for the no-action and technology-adoption baselines. The costs to reduce 1 tCO₂eq are presented for a discount rate of 10 percent and a tax rate of 40 percent.

Table 11-3: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	8.13	8.13	8.13	8.13	8.13
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.47	0.47	0.47	0.47	0.47
China	0.00	1.65	1.65	1.65	1.65	1.65
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	1.01	1.01	1.01	1.01	1.01
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.11	0.11	0.11	0.11	0.11
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	1.43	1.43	1.43	1.43	1.43
OECD	0.00	6.70	6.70	6.70	6.70	6.70
Russian Federation	0.00	1.20	1.20	1.20	1.20	1.20
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	4.50	4.50	4.50	4.50	4.50
World Total	0.00	11.94	11.94	11.94	11.94	11.94

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 11-4: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—No-Action Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	11.13	11.13	11.13	11.13	11.13
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.70	0.70	0.70	0.70	0.70
China	0.00	3.74	3.74	3.74	3.74	3.74
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	1.54	1.54	1.54	1.54	1.54
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.18	0.18	0.18	0.18	0.18
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	1.78	1.78	1.78	1.78	1.78
OECD	0.00	9.35	9.35	9.35	9.35	9.35
Russian Federation	0.00	1.51	1.51	1.51	1.51	1.51
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	6.26	6.26	6.26	6.26	6.26
World Total	0.00	17.85	17.85	17.85	17.85	17.85

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 11-5: Emissions Reductions in 2010 and Breakeven Costs (\$/tCO₂eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2010					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	1.54	1.54	1.54	1.54	1.54
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.05	0.05	0.05	0.05	0.05
China	0.00	1.65	1.65	1.65	1.65	1.65
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.10	0.10	0.10	0.10	0.10
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.01	0.01	0.01	0.01	0.01
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	0.14	0.14	0.14	0.14	0.14
OECD	0.00	1.39	1.39	1.39	1.39	1.39
Russian Federation	0.00	0.12	0.12	0.12	0.12	0.12
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	1.17	1.17	1.17	1.17	1.17
World Total	0.00	3.40	3.40	3.40	3.40	3.40

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 11-6: Emissions Reductions in 2020 and Breakeven Costs (\$/tCO₂eq) for Mg Production at 10% Discount Rate, 40% Tax Rate (MtCO₂eq)—Technology-Adoption Baseline

Country/Region	2020					
	\$0	\$15	\$30	\$45	\$60	>\$60
Africa	0.00	0.00	0.00	0.00	0.00	0.00
Annex I	0.00	0.90	0.90	0.90	0.90	0.90
Australia/New Zealand	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	3.74	3.74	3.74	3.74	3.74
Eastern Europe	0.00	0.00	0.00	0.00	0.00	0.00
EU-15	0.00	0.00	0.00	0.00	0.00	0.00
India	0.00	0.00	0.00	0.00	0.00	0.00
Japan	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.00	0.00	0.00	0.00	0.00	0.00
Non-OECD Annex I	0.00	0.00	0.00	0.00	0.00	0.00
OECD	0.00	0.90	0.90	0.90	0.90	0.90
Russian Federation	0.00	0.00	0.00	0.00	0.00	0.00
South & SE Asia	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	0.90	0.90	0.90	0.90	0.90
World Total	0.00	4.63	4.63	4.63	4.63	4.63

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 11-7: Emissions Reduction and Costs in 2020—No-Action Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
SO ₂ replacement	\$0.53	\$0.79	10.90	60.3%	10.90	60.3%
Fluorinated covergas	\$1.21	\$1.48	6.95	38.5%	17.85	98.8%

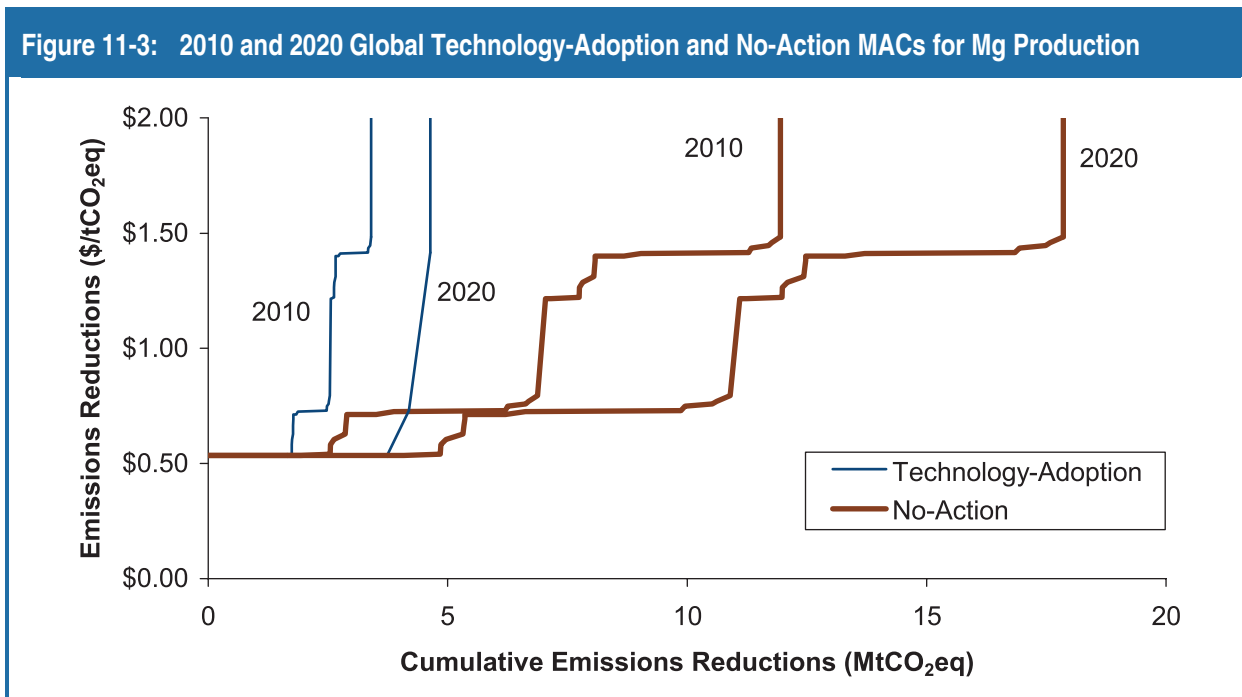
Table 11-8: Emissions Reduction and Costs in 2020—Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO ₂ eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO ₂ eq)	Cumulative Reduction from 2020 Baseline (%)
	Low	High				
SO ₂ replacement	\$0.53	\$0.79	4.19	86.6%	4.19	86.6%
Fluorinated covergas	\$1.21	\$1.48	0.44	9.2%	4.63	95.8%

IV.11.3.2 Global and Regional MACs and Analysis

This section discusses the results from the MAC analysis of the world and selected countries and regions, including China, Japan, the United States, EU-15, other OECD, and the rest of the world.

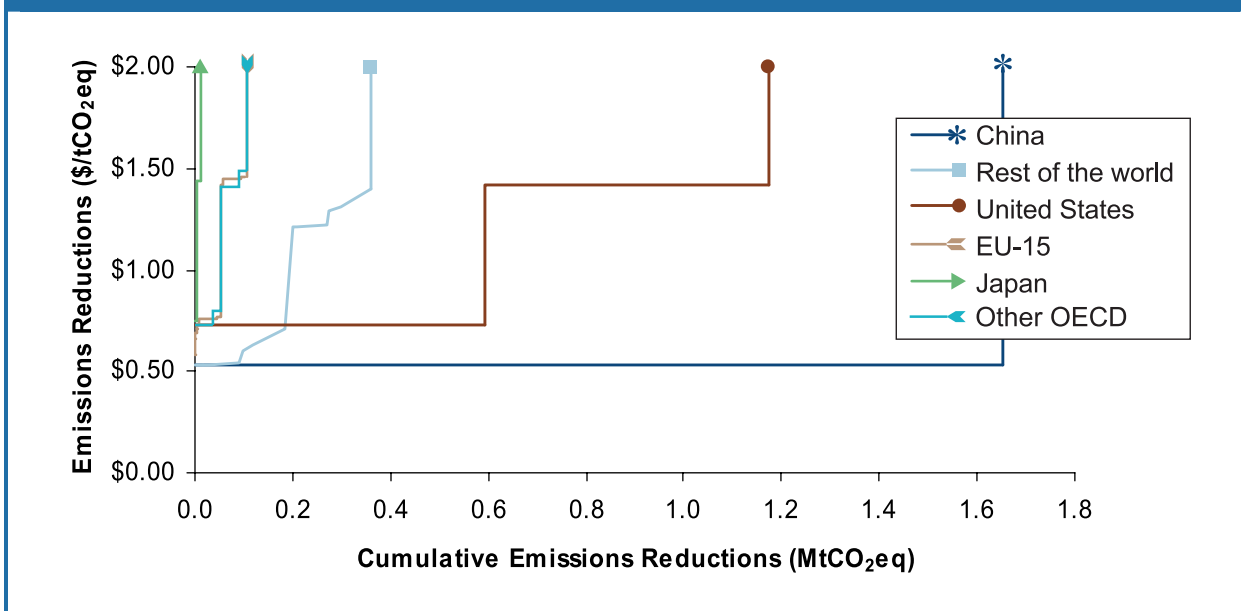
Figure 11-3 presents the 2010 and 2020 global technology-adoption and no-action MACs for Mg production and processing. The technology-adoption MACs reflect the successful achievement of the IMA goal to eliminate SF_6 use by 2011. Although it is expected that the majority of SF_6 use will be eliminated by 2011, some use is assumed to continue to occur in the United States and China in 2020. The rightward shift in technology-adoption MACs between 2010 and 2020 primarily reflects the continuing growth of Chinese primary production and die-casting and their associated use of SF_6 as a cover gas.



In contrast, the no-action MACs assume that no technology adoptions and/or preventive maintenance steps are taken to reduce emissions. Because the SF_6 emissions intensities (i.e., SF_6 emissions per unit of Mg production) for primary, secondary, and casting production are assumed to remain constant between 2010 and 2020, increasing emissions (reflected by the rightward shift in the 2020 MAC) are driven by continuing positive production growth in all regions, particularly the United States and China.

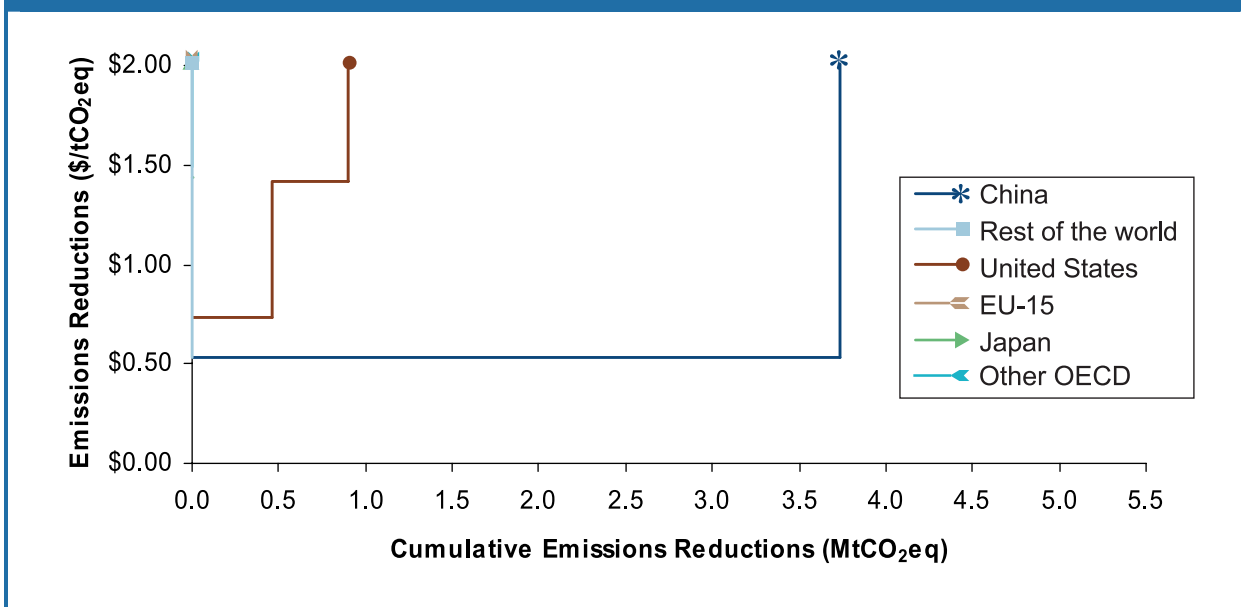
Figures 11-4 and 11-5 present 2010 and 2020 regional technology-adoption MACs for China, Japan, the United States, EU-15, other OECD, and the rest of the world. The 2010 MAC represents potential emissions reductions and associated costs for global Mg producers and processors a year before the assumed successful adoption of the IMA goal. Consequently, the small reductions associated with EU-15 countries, Japan, other OECD (e.g., Norway and Canada), and the rest of the world (e.g., Brazil, Taiwan, Israel, the Russian Federation, Ukraine, and Kazakhstan) reflect this assumption. In China and the United States, some Mg casters and recyclers have not committed to the IMA goal; consequently, significant emissions reductions are still achievable through implementation of abatement options. In China, SO_2 is considered the only abatement option, while in the United States, both SO_2 and alternate fluorinated gases are assumed to be available. In all regions, SO_2 is estimated to be less expensive than fluorinated gases such as Novec 612 and HFC-134a.

Figure 11-4: 2010 Regional Technology-Adoption MACs



EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 11-5: 2020 Regional Technology-Adoption MACs



EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

In 2020, for the technology-adoption MACs, reductions are only available for the United States and China. For all other Mg producing countries, it is assumed that the IMA goal has been successfully achieved. In the United States, although abatement costs are the same as in 2010, the curve has shifted to the left. This reflects the fact that primary production and a majority of casting companies in the United States have agreed to meet the IMA goal; consequently, the only emissions available for abatement in 2020 are from the remaining casting and recycling firms that have not committed to phaseout SF_6 use. In China, carbon costs for SO_2 abatement are assumed to be the same as in 2010 (\$0.53/tCO₂eq); however, the

MAC has shifted to the right because of increased use of SF_6 during primary production and casting in the baseline, which is projected to grow significantly to meet local demand.

IV.11.3.3 Uncertainties and Limitations

Uncertainties and limitations persist despite attempts to incorporate all publicly available information on international Mg production and processing. Additional information would improve the accuracy of the MACs.

Mg Production and Processing

Although historical primary production statistics are available for most countries, a source of uncertainty is the limited information on historical country-specific secondary and die-casting production and Chinese primary production. There is also limited information on country-specific SF_6 usage rates (i.e., emissions factors); these rates are likely to vary by facility and country because of differing operational practices and manufacturing processes. Additionally, the current methodology assumes that all SF_6 gas used is emitted into the atmosphere; however, recent studies (Bartos et al., 2003; USEPA, 2004) indicate that some SF_6 degradation may occur (e.g., 10 percent) during magnesium melt protection. As a result, current SF_6 emissions factors may be higher than actual emissions rates. Improved country-specific production-level data and growth projections and SF_6 usage rates would improve the baseline emissions estimates to which the abatement options are applied.

IMA SF_6 Reduction Goal

In the technology-adoption baseline, emissions projections assume attainment of the IMA goal, which is the elimination by 2011 of SF_6 use in Mg production and processing operations in all countries except China and the United States where some processors have not committed to the goal. Because there is limited information on country-specific implementation of alternate cover gas practices, at the current time, it is unclear whether this goal will be achieved. Improved information on country-specific practices would improve modeling of the IMA goal.

Implementation of Alternate Cover Gases

For most countries, the MACs assume a 50/50 percent market penetration of SO_2 and fluorinated (Novec 612 and HFC-134a) cover gases. Because of limited information, it is unclear if this is an accurate representation of actual future industry application of these technologies. However, because the reduction efficiencies for the abatement options are high (i.e., 100 percent for SO_2 and an average of 97 percent for fluorinated gases), the uncertainty in the reduction achieved will be low. Recent USEPA studies have noted that both Novec 612 and HFC-134a undergo significant degradation while providing melt protection; consequently, reduction efficiencies may be even higher than those currently used (i.e., 99.9 percent) (USEPA, 2004).

Costs of Alternative Fluorinated Cover Gases

The capital costs associated with adopting the various fluorinated gases are likely to vary, with some gases requiring relatively little retrofitting of the SF_6 cover gas system and others requiring more. This analysis conservatively assumes that, on average, the capital costs of replacing SF_6 with fluorinated gases will be the same as the capital costs of replacing SF_6 with SO_2 , which includes costs for developing a special distributed feed system and process and implementing pollution control systems. Not all fluorinated gases are likely to require such systems. Thus, in some cases, this analysis probably overestimates the costs of adopting alternative fluorinated gases.

Adjusting Costs for Specific Domestic Situations

The annual and capital costs associated with implementing the SO₂ abatement option are based on information provided in the *Powering GHG Reduction through Technology Advancements* report by Environment Canada (1998). Although adjustments for annual costs are provided to account for differing country-specific labor costs, no adjustments for capital costs are applied. This is a potential source of uncertainty because countries other than Canada may be faced with higher costs due to transportation and tariffs associated with purchasing the technology from abroad or could be faced with lower costs due to domestic production of these technologies.

Country-Specific Tax and Discount Rates

A single tax rate is applied to the Mg sector in all countries to calculate the annual benefits of each technology; however, tax rates can vary across countries. Similarly, the discount rate may vary by country. Improving the level of country-specific detail will help analysts more accurately calculate benefits and hence breakeven prices.

IV.11.4 References

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Section IV: Industrial Processes Sector Appendixes

Appendixes for this section are available for download from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

V. Agriculture

Section V presents international emission baselines and marginal abatement curves (MACs) for all significant agricultural non-CO₂ sources. There are subsections that address emissions and mitigation options for croplands, rice cultivation, and livestock. These sources are associated with methane (CH₄) and nitrous oxide (N₂O) emissions, as well as soil carbon. MAC data are focused on percentage reduction values from baseline emissions. These data can be downloaded in spreadsheet format from the USEPA's Web site at <<http://www.epa.gov/nonco2/econ-inv/international.html>>.

Section V—Agriculture is organized as follows:

- V.1 Introduction and Background
- V.2. Emissions Characterization, Baselines, and Mitigation Scenarios
 - V.2.1 Croplands (N₂O and soil carbon)
 - V.2.2 Rice (CH₄, N₂O and soil carbon)
 - V.2.3 Livestock (CH₄ and N₂O)
- V.3 Results
 - V.3.1 Estimating Average Costs and Constructing Abatement Curves
 - V.3.2 Croplands
 - V.3.3 Rice
 - V.3.4 Livestock
 - V.3.5 Total Agriculture
 - V.3.6 Agricultural Commodity Market Impacts
- V.4 Conclusions

V.1 Introduction and Background

Agricultural activities currently generate the largest share, 63 percent, of the world's anthropogenic non-carbon dioxide (non-CO₂) emissions (84 percent of nitrous oxide [N₂O] and 52 percent of methane [CH₄]), and make up roughly 15 percent of all anthropogenic greenhouse gas emissions (U.S. Environmental Protection Agency [USEPA], 2006; Prentice et al., 2001).¹ Agricultural greenhouse gas emissions are projected to increase significantly over the next 20 years, especially in Asia, Latin America, and Africa, because of increased demand for agricultural products as a result of population growth; rising per capita caloric intake; and changing diet preferences, such as an increased consumption of meat and dairy products over grains and vegetables (see Food and Agriculture Organization [FAO], 2002). Agricultural soil N₂O emissions are projected to increase 37 percent by 2020 compared with 2000 levels, enteric livestock CH₄ emissions are projected to increase 30 percent, manure CH₄ and N₂O to increase 24 percent,² and rice CH₄ to increase 22 percent (USEPA, 2006).

The agricultural sector presents unique challenges to developing greenhouse gas mitigation cost estimates at regional and international scales. First, there is a high degree of spatial and temporal heterogeneity in biophysical and management conditions and thus in resulting greenhouse gas emissions, which are rarely directly monitored. This fact makes it challenging to extrapolate the greenhouse gas and cost implications of farm-level mitigation analyses, the scale at which much of the literature on this subject is found. Any large-scale mitigation analysis should emphasize the broad trends and direction and magnitude of changes, which requires some trade-off in accuracy for very small spatial (e.g., individual farms) and temporal (e.g., days and seasons) scales. Second, there is a paucity of regional cost data from which one can estimate the implications of implementing greenhouse gas mitigation practices, in terms of changes in inputs, revenue, and labor. Third, estimating the expected level of adoption of the mitigation options in response to financial incentives (e.g., carbon price) or, alternatively, in response to extension services with greenhouse gas reduction objectives, is difficult given the information and cultural barriers to adoption in different regions.

Nevertheless, agricultural net greenhouse gas and non-CO₂ mitigation analyses have been developed for several countries and the world. Some analyses include a relatively comprehensive set of greenhouse gas mitigation options with a dynamic economic and biophysical representation of the agricultural and forest sectors (see USEPA [2005a] for the United States). Others target individual agricultural emissions sources with static, engineering mitigation estimation methods (see Kroeze and Mosier [1999] for global cropland N₂O and enteric CH₄ emissions and Reimer and Freund [1999] for global rice emissions; see also Table 3.27 in Moomaw et al. [2001] of IPCC Working Group III). The USEPA supported the development of global mitigation estimates for cropland N₂O, livestock enteric and manure CH₄, and rice CH₄ (DeAngelo et al., 2006) that were then incorporated into the Energy Modeling Forum-21 (EMF-21) study of global multigas mitigation options (van Vuuren et al. [2006]). This report improves on the agricultural analysis conducted for EMF-21 in a number of areas.

¹ This value compares the International Panel on Climate Change (IPCC) (Prentice et al., 2001) estimate of gross annual CO₂ emissions from fossil fuel combustion, cement manufacturing, and land-use change with the USEPA (2006) estimate of all anthropogenic non-CO₂ emissions. Fossil fuel CO₂ emissions associated with agriculture (e.g., on-farm equipment, fertilizer production) are not assigned to the agricultural sector in this estimate.

² The estimated increase of manure CH₄ and N₂O emissions represents a joint estimate based on CO₂ equivalent units using global warming potentials (GWPs) from the IPCC Second Assessment Report.

V.1.1 Brief Points of Comparison with Other Non-CO₂ Emissions Sectors

A few points about how baseline assumptions and methods for agriculture compare with those in other non-CO₂ sectors of this report are in order. First, baseline emissions projections used in this section are not entirely consistent with baseline projections developed by the USEPA (2006). This is the case for cropland N₂O and rice CH₄ emissions, where separate baseline emissions projections are developed with process-based models. These models, described later in this section, are also used for the mitigation scenarios, so that assumptions and all underlying activity data on both the baseline and mitigation sides of the equation are consistent.

Second, although the focus of this report is on the non-CO₂ greenhouse gases, soil carbon is included in the agricultural analysis. Including soil carbon is important for agriculture because it provides a more comprehensive picture of the net greenhouse gas effects of mitigation options that primarily target N₂O and CH₄.

Third, the agricultural analysis, like other sectors in this report, presents marginal abatement curves (MACs) by region, for the 2000 to 2020 period, showing the technical, net greenhouse gas mitigation potential at various levels of U.S. dollars (USD) per tonne of CO₂ equivalent (\$/tCO₂eq), representing the breakeven price of each mitigation option. The approach used to estimate the technical mitigation potential is similar to that used in other sectors—a bottom-up, engineering approach. However, the agricultural analysis illustrates the sensitivity of the mitigation estimates to potential economic market feedbacks as a result of adopting the mitigation options (i.e., showing the effects of simultaneous changes in crop yields, livestock productivity, commodity prices, cropland area, livestock herd size, and emissions).

V.1.2 Previous Estimates for EMF-21 and New Improvements

Previously, the USEPA helped produce a non-CO₂ mitigation analysis for world agriculture (DeAngelo et al., 2006) to assist climate-economic and integrated assessment modelers who participated in the EMF-21 study represent the agricultural sector. The study generated MACs by major world regions for cropland N₂O, livestock enteric CH₄, manure CH₄, and rice CH₄ for 2010. This analysis used a static, engineering approach by relying on literature sources to identify the non-CO₂ reductions associated with each mitigation option, extrapolating those results beyond their original scale of analysis (farm, region, or nation) to other world regions, estimating regionally specific changes in input costs with FAOSTAT and other data sources, and adjusting the extent to which each mitigation option applied to different regions. Summary results of this previous analysis and how they compare with the current analysis are presented in Appendix P.

The current analysis uses new approaches to improve on the previous EMF-21 study in a number of areas. First, biophysical, process-based models (DAYCENT and DNDC) are used to better capture the net greenhouse gas and yield effects of the cropland and rice emissions baseline and mitigation scenarios. The previous analysis estimated the single, dominant gas effects only (e.g., no N₂O or soil carbon effects for rice CH₄ mitigation practices). Furthermore, process-based models better reflect the heterogeneous emissions and yield effects over space and time of adopting mitigation practices, whereas the previous analysis usually assumed a uniform percentage change in emissions and/or yields across regions. The process-based models also ensure greater consistency in underlying assumptions and activity data between baseline and mitigation scenarios. For example, when emissions projections are estimated with IPCC Tier I default methodologies, it is not always possible to identify what underlying management

practices are taking place, which in turn makes it difficult to ascertain if the chosen mitigation options are indeed additional to baseline management practices.

New mitigation options are assessed (e.g., slow-release fertilizers, nitrogen inhibitors, and no till), and more detailed, less aggregated results are provided for individual crop types (e.g., maize, wheat, and soybeans) under both irrigated and rain-fed conditions. Lastly, sensitivity experiments using a global agricultural trade model (IMPACT of the International Food Policy Research Institute [IFPRI]) are conducted to assess the agricultural commodity market effects of adopting the mitigation options.

V.2 Emissions Characterization, Baselines, and Mitigation Scenarios

V.2.1 Croplands (N₂O and Soil Carbon)

V.2.1.1 Cropland N₂O and Soil Carbon Emissions Characterization

N₂O is typically the dominant greenhouse gas source from agricultural systems and is produced naturally in soils through the processes of nitrification and denitrification. These are soil microbial processes whereby ammonium (NH₃) is reduced to nitrate (NO₃) under aerobic or oxygen-rich conditions (nitrification), and nitrate is reduced to molecular nitrogen (N₂) under anaerobic or oxygen-poor conditions (denitrification). A number of activities add nitrogen to soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N₂O emitted to the atmosphere. Activities may add nitrogen to soils either directly or indirectly. Direct additions occur through nitrogen fertilizer use, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops and forages, retention of crop residues, and cultivation of histosols (i.e., soils with high organic-matter content, also known as organic soils). Indirect emissions occur through volatilization and subsequent atmospheric deposition of applied nitrogen, as well as through surface runoff and leaching of applied nitrogen into groundwater and surface water.

Other soil management activities, such as irrigation, drainage, tillage practices, and fallowing of land, can also affect fluxes of N₂O, as well as soil carbon and fossil fuel CO₂ emissions. Fossil fuel CO₂ emissions can be generated on-farm by agricultural equipment and off-farm or upstream through the energy-intensive production of fertilizers.³ These fossil fuel CO₂ emissions are not included in this study; thus some net emissions reduction benefits of the mitigation options are likely to be underestimated in this report.⁴

Agricultural soil carbon emissions and/or sequestration tend to be less dominant than N₂O emissions in terms of the net greenhouse gas picture under baseline conditions; however, enhancing soil carbon sequestration represents a significant greenhouse gas mitigation option, potentially more viable than N₂O reductions (see USEPA [2005a]). Croplands often emit CO₂ as a result of conventional tillage practices and other soil disturbances. This occurs when soils containing organic matter that would otherwise be protected by vegetative cover are exposed to the air through tillage disturbances and become susceptible to decomposition. Conservation tillage—defined in the United States as any tillage system that maintains at least 30 percent of ground covered by crop residue after planting (Conservation Technology Information Center [CTIC], 1994)—eliminates one or several practices associated with conventional tillage, such as turning soils over with a moldboard plow and mixing soils with a disc plow (Lal et al.,

³ Under IPCC greenhouse gas inventory reporting guidelines and in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* reported by the USEPA, these fossil fuel CO₂ emissions are reported as energy-sector not agricultural-sector emissions.

⁴ In the USEPA (2005a), the FASOM-GHG model of U.S. forestry and agriculture shows that on-farm and upstream fossil fuel CO₂ emissions associated with crop production are roughly 40 percent of the size of the joint CH₄ and N₂O emissions in agriculture, on a CO₂-equivalent basis. The DAYCENT modelers for this report assumed that for every unit of nitrogen fertilizer applied, 0.8 units of CO₂ were generated from fertilizer manufacturing, though these numbers were intentionally excluded from this report to maintain consistency across emissions categories.

1998). Conservation tillage, including no-till, allows crop residues to remain on the soil surface as protection against erosion.

Lastly, seasonal temperature and precipitation changes, as well as regional climate variability, influence rates of both soil N₂O and carbon emissions.

V.2.1.2 DAYCENT Baseline Estimates of Cropland N₂O, Soil Carbon, and Yields

The DAYCENT model is used to estimate baseline and mitigation scenario emissions of N₂O and soil carbon for a significant share of the world's nonrice croplands. (DAYCENT, rather than IPCC default values, is also the tool now used to estimate the majority of agricultural soil N₂O emissions for the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, reported by the USEPA). Use of DAYCENT offers the advantage of a consistent methodology and tool across regions and between the baseline and mitigation scenarios. The DAYCENT model and emissions baseline methodologies are described briefly here, and further details are provided in Appendix Q.

The DAYCENT model (Del Grosso et al., 2001; Parton et al., 1998) is a process-based model that simulates crop growth, soil organic-matter decomposition, greenhouse gas fluxes, nitrogen deposited by grazing animals, and other biogeochemical processes using daily climate data, land management information, and soil physical properties. N₂O emissions estimated by DAYCENT account for nitrogen additions, crop type, irrigation, and other factors and capture both direct (through fertilizer applications) and indirect (through volatilization and leaching) N₂O emissions.

Global baseline N₂O emissions for this report are estimated from DAYCENT to be 799 MtCO₂eq in 2000, 795 MtCO₂eq in 2010, and 859 MtCO₂eq in 2020. With the net effects of soil carbon, global net greenhouse gas estimates are 839 MtCO₂eq, 830 MtCO₂eq, and 893 MtCO₂eq for 2000, 2010, and 2020, respectively. These estimates represent the mean of decadal averages (e.g., 1996 to 2005 mean for reported year 2000). Emissions estimates for individual key countries and regions are provided in Table 1-1 (see Section V.1.3.2 for additional baseline data).

Table 1-1: DAYCENT N₂O and Soil Carbon Estimates for 2000, 2010, and 2020 by Key Region (MtCO₂eq/yr)

Region	2000		2010		2020	
	N ₂ O	Soil Carbon	N ₂ O	Soil Carbon	N ₂ O	Soil Carbon
United States	164	3	176	2	197	3
EU-15	95	-4	98	-5	107	-6
Eastern Europe	37	2	37	2	39	2
FSU	187	26	127	30	126	36
Mexico	14	1	16	1	17	>0
Brazil	28	0	30	0	30	0
India	69	-3	74	-4	78	-5
China	84	7	95	3	105	-1

EU-15 = European Union; FSU = Former Soviet Union.

Note: Negative numbers indicate net sequestration.

As described below, the cropland coverage for the DAYCENT simulations is incomplete. Therefore, the baseline estimates from DAYCENT are intended to serve as the foundation from which to assess the general implications of mitigation scenarios. The DAYCENT baseline estimates are not intended to serve as independent national and global inventory estimates, which can be found elsewhere in the literature (USEPA 2006; USEPA 2005b; Robertson 2004; IPCC 2001; Ehhalt et al., 2001; Mosier et al., 1998).

Appendix S describes how the DAYCENT N₂O emissions baseline estimates compare with the USEPA's (2006) more comprehensive estimates.

DAYCENT explicitly simulates the major crop types only: maize, spring and winter wheat, and soybeans. However, analogous crops are added to these major crop types (e.g., rye, barely, and oats with wheat; millet and sorghum with maize) to increase the coverage of cropland area and to capture a higher portion of nitrogenous fertilizer applications. Grazing-land emissions are not included, and emissions due to residue burning are not included. For these reasons, the DAYCENT baseline N₂O estimates are generally lower than other published inventory studies for national and world total N₂O emissions.

DAYCENT simulations for maize, wheat, and soybean areas are run under both irrigated and rain-fed conditions.⁵ The relative portion of maize, wheat, and soybean areas under irrigated and rain-fed conditions are provided by IFPRI and vary by region and over time.

Underlying data for the emissions estimates include global data sets of weather, soils, cropland area, and native vegetation, mapped to an approximate 2° × 2° resolution. Daily weather data (i.e., precipitation and maximum and minimum temperatures) from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction for the 1991 to 2000 period are used under both baseline and mitigation options; therefore, there is no explicit assumption about anthropogenic climate change for the 2000 to 2020 period. Soils data include texture percentages of clay, sand, and silt and come from FAO/UNESCO (1996). Histosols, a source of N₂O, are not included in the simulations. Cropland distribution and the fractional area of specific crops are taken from both the International Geosphere Biosphere Programme (IGBP) land cover classification (Belward et al., 1999; Belward, 1996) and the Global Land Cover (GLC) data set of Leff et al. (2004).

Cropland area is assumed to remain constant over time in the DAYCENT simulations under both baseline and mitigation options (the same assumption is held for rice areas with the DNDC simulations). The subject of changing area in response to market feedbacks due to the implementation of mitigation options is discussed in Section V.1.3.6.

In addition to simulating N₂O emissions from mineral cropland soils, a DAYCENT simulation was performed for those same areas as though they were covered by native vegetation and never cultivated (using *potential* vegetation from Cramer et al. [1999] and Melillo et al. [1993]), so that anthropogenic emissions are isolated from natural background emissions. Therefore, all reported emissions estimates

Box 1-1: DAYCENT Estimates of U.S. Agricultural N₂O Emissions in This Report versus Inventory

The annual *Inventory of Greenhouse Gas Emissions and Sinks*, reported by the USEPA, now uses the DAYCENT model to estimate the majority of agricultural soil N₂O emissions. Though DAYCENT is used in this report and provides estimates for U.S. agricultural soil N₂O emissions under baseline and mitigation scenarios, the U.S. estimates in this report are not the same as the U.S. estimates in the Inventory. This is because the Inventory uses input data specific to the United States, while the input data used by DAYCENT in this report come from global data sets to provide as much consistency as possible across regions, including the United States.

⁵ Rain-fed conditions mean that the crop receives no extra water in addition to rainfall and the resultant water stored in the soil. To simulate irrigation, extra water is added, if necessary, to bring soil water content to field capacity once per week for 20 weeks during the growing season. This minimizes or eliminates plant water stress and is an assumption consistent with the fact that farmers typically irrigate only when necessary because irrigation requires resources.

under both baseline and mitigation scenarios from croplands represent anthropogenic emissions separated from natural background emissions.⁶

Synthetic nitrogenous fertilization rates are based on globally uniform relationships with current and projected production of the major crop types by region. Current and historic nitrogenous fertilization data for each region are from FAOSTAT (2004b) and the International Fertilizer Industry Association (IFA) (2002). Current nitrogenous fertilization rates (kg/hectare) were assumed to be the same as 1998 levels, and projected rates were scaled from this base. Projected fertilization rates for wheat and maize were taken from regression equations based on crop production from FAO (2000); for soybeans, an analogous regression equation was developed using a combination of FAOSTAT (2004b) and IFA (2002) (see Appendix Q). Regionally specific projections of crop yields from IFPRI for 2010 and 2020 are used with these equations to derive future fertilization rates. Crop area is assumed to remain constant for the DAYCENT simulations. Increases in N₂O out to 2020 for most regions (see Table 1-1) are therefore the result of increasing rates of fertilization based on yield projections. All baseline fertilizer applications for all regions are assumed to be administered in one application.

Organic-matter fertilizer additions are assumed to be a function of animal numbers by region. Historical trends in organic fertilizer use were calculated from animal numbers reported by FAOSTAT (2004a), using IPCC default factors concerning region-specific average nitrogen excretion per animal, and the percentage of nitrogen distributed among waste management practices (see Appendix Q for IPCC default factors). Projections of manure nitrogen are taken from underlying activity data used for USEPA (2006).

Nonspatial data (such as planting date and fertilizer application rates) were assigned as point values for each region or country and were assumed to be the same within each region. Global maps of 2° × 2° resolution for baseline N₂O emissions estimated by DAYCENT for areas of wheat, maize, and soybeans are presented in Appendix Q (under rain-fed conditions only).

V.2.1.3 Mitigation Options for Cropland N₂O and Soil Carbon Emissions

Mitigation options for croplands have been identified that could decrease N₂O emissions, often the result of applying fertilizer that exceeds crop demand, while maintaining yields (e.g., Mosier et al., 2002). Mitigation options are chosen with this goal in mind. Options are listed in Table 1-2. The soil N₂O mitigation options involve either more efficient (or simply reduced) application of nitrogen-based fertilizers (e.g., adding nitrification inhibitors; using split fertilization; reducing baseline nitrogen fertilization by 10, 20, or 30 percent) or adoption of no-till cultivation methods. Because the focus of this report is on the non-CO₂ greenhouse gas emissions, additional options that might increase soil carbon (e.g., reduced fallow periods, different cropping mix) are not considered.

These mitigation options are simulated by DAYCENT and resulting crop yields (of wheat, maize, and soybeans), and emissions effects are compared with the DAYCENT baseline, as described above. Though all mitigation options are represented in the final MACs, DAYCENT simulates only one mitigation option at a time, assuming that each mitigation option is implemented on all croplands in 2000 and continuously until 2020. No mitigation options are implemented simultaneously on the same croplands, or on different portions of the croplands, within DAYCENT.

⁶ This approach of isolating anthropogenic emissions from natural background emissions is also used when the DAYCENT model is applied to estimate anthropogenic N₂O emissions from agricultural soils for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, reported by the USEPA.

Table 1-2: Cropland N₂O and Soil Carbon Mitigation Options Run Through DAYCENT

Mitigation Option	Description	Greenhouse Gas Effects
Split fertilization	Application of same amount of nitrogen fertilizer as in baseline but divided into three smaller increments during crop uptake period to better match nitrogen application with crop demand and reduce nitrogen availability for leaching, nitrification, denitrification, and volatilization.	N ₂ O, some soil carbon
Simple fertilization reduction—10 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 10 percent.	N ₂ O, some soil carbon
Simple fertilization reduction—20 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 20 percent.	N ₂ O, some soil carbon
Simple fertilization reduction—30 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 30 percent.	N ₂ O, some soil carbon
Nitrification inhibitor	Reduces conversion of ammonium to NO ₃ , which slows the immediate availability of nitrate (nitrate is water soluble). The inhibition of nitrification reduces nitrogen loss and increases overall plant uptake.	N ₂ O, some soil carbon
No-till	Conversion from conventional tillage to no till, where soils are disturbed less and more crop residue is retained.	Soil carbon, some N ₂ O

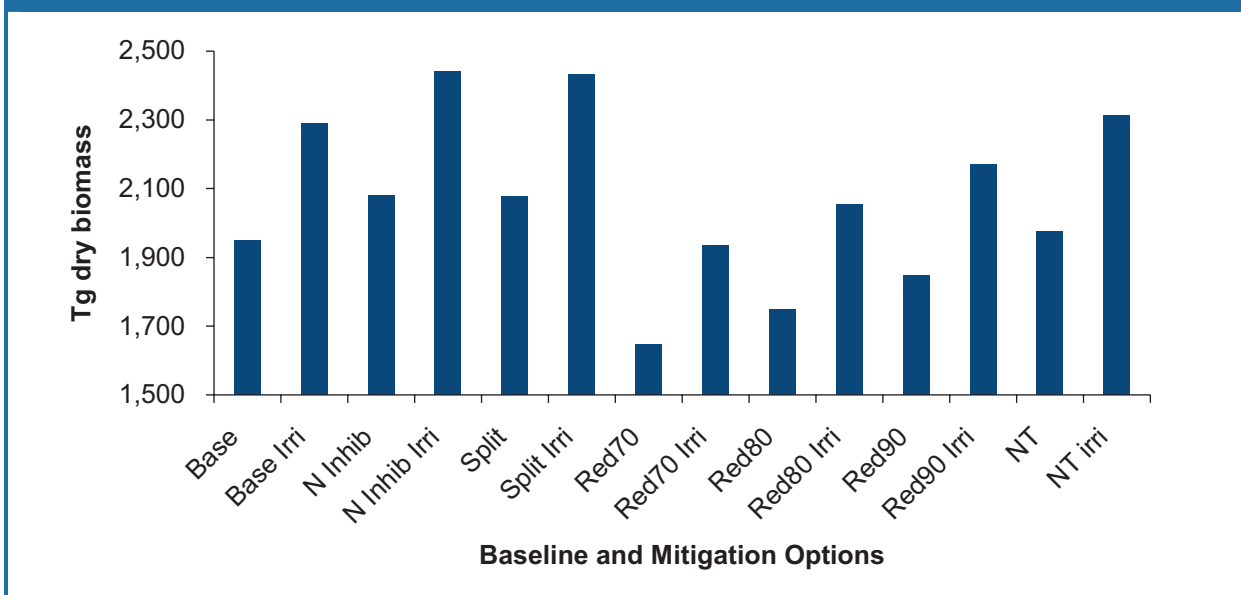
As in the baseline scenario, each DAYCENT mitigation simulation is run according to the relative portions of maize, wheat, and soybean areas under either irrigated or rain-fed management.

A number of mitigation options are found to increase net greenhouse gas emissions relative to the baseline depending on crop, management, region, and time period. These options are removed to estimate and construct the abatement curves. The number of options that increase net emissions grows from the 2000 to the 2010 to the 2020 period. All of these options occur on either wheat or maize croplands, are spread over most regions of the world, and predominantly involve reducing baseline nitrogen fertilizers. The primary reason why decreasing nitrogen fertilizer use leads to an increase in net GHG in some regions is a decrease in soil carbon—due to lower plant growth from the fertilizer reductions and hence less residue returning to the soil—which more than compensates for the lower N₂O emissions. A small number of Asian regions experience an increase in emissions for the split-fertilization option, which can occur if more frequent (but smaller) fertilizer applications coincide with rainy periods; however, the timing of the applications for this option was assumed to be uniform across regions. In practice, farmers would time fertilizer applications based on their local weather conditions and on plant growth stages. In addition, some of the no-till scenarios in Western Europe increase net emissions; this is primarily because no till allows for greater soil water content and enhances denitrification to produce N₂O emissions.

V.2.1.4 DAYCENT Results for Changes in Cropland N₂O, Soil Carbon, and Yields

Figure 1-1 summarizes total global production of the major crops of wheat, maize, and soybeans under baseline and mitigation scenarios, holding area constant. DAYCENT simulations were performed for both irrigated and nonirrigated conditions. In every case, production is higher with irrigation, as expected. All three of the options that were effective in reducing emissions (i.e., nitrification inhibitors, split-fertilization, and conversion to no till) simultaneously increased production. The three options that involved reduced fertilization, on the other hand, resulted in substantial reductions in production.

Figure 1-1: Global Cropland Yields for Baseline and Mitigation Options Estimated by DAYCENT, 2010^a



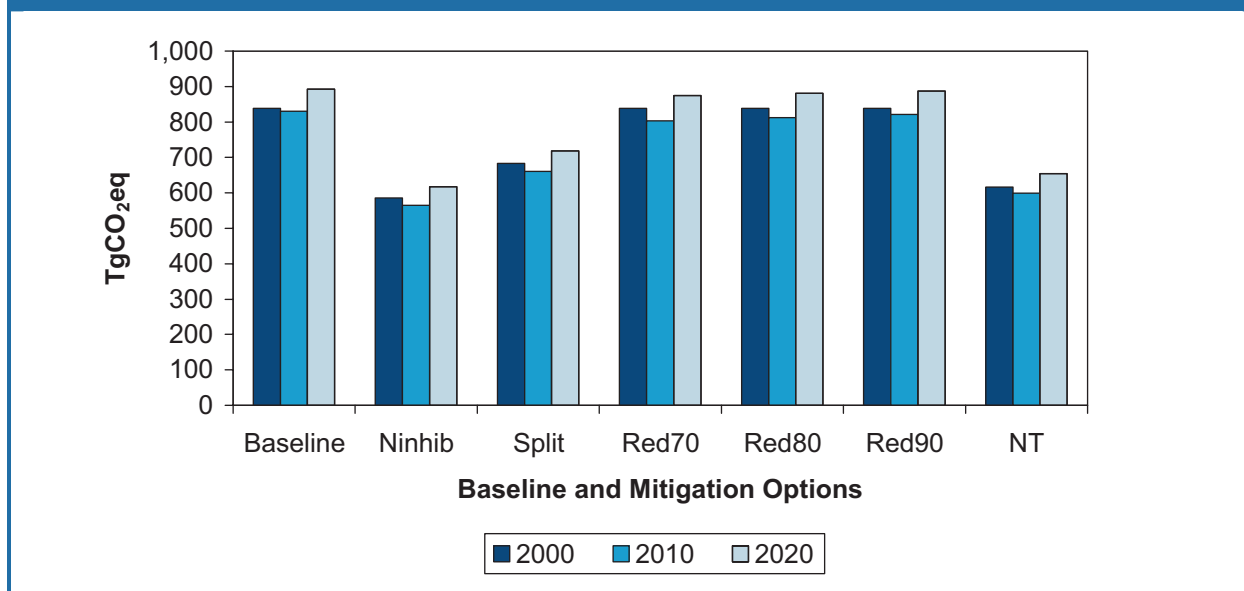
Note: This figure shows total global production of wheat, maize, and soybeans—the three major crops modeled using DAYCENT—simulated under the baseline and mitigation options.

^a Ninhib—addition of nitrification inhibitor (irrigated and nonirrigated).
 Split—split fertilization, dividing fertilizer applications into three smaller increments.
 Red70—reduction of nitrogen-based fertilizer to 70 percent of baseline.
 Red80—reduction of nitrogen-based fertilizer to 80 percent of baseline.
 Red90—reduction of nitrogen-based fertilizer to 90 percent of baseline.

Reduced nitrogen fertilizer leads to reduced yields because plant growth rates, and hence crop yields, are highly sensitive to nutrient supply in DAYCENT. That is, DAYCENT assumes that plant growth is limited by nutrient availability, as well as by water and temperature. Nitrification inhibitors and split fertilizer caused the largest increase in yields because both of these options maintain higher nitrogen availability for plants. Nitrification inhibitors keep more nitrogen in the root zone for two reasons: less nitrogen is lost from the soil as nitrogen gas and, because the conversion of ammonium (NH₄) to NO₃ is inhibited, less NO₃ is leached below the root zone. Split-nitrogen application increases plant-available nitrogen, because nitrogen supply is more synchronized with plant-nitrogen demand. Higher plant-nitrogen uptake also reduces nitrogen losses from nitrification, denitrification, and leaching, although to a lesser extent than the nitrification inhibitor, for the reasons discussed above.

As shown in Figure 1-2, DAYCENT simulations for corn, soy, and wheat suggest that using nitrification inhibitors and no-till cultivation lead to the largest reduction in net greenhouse gas emissions at the global scale. Surprisingly, reduced nitrogen fertilizer leads to net emissions similar to the baseline scenario. The decrease in crop production associated with reduced fertilizer applications leads to reduced

Figure 1-2: Global Net Greenhouse Gas (N₂O and Soil Carbon) Cropland Emissions Estimated by DAYCENT under Baseline and Mitigation Scenarios^a



^a Ninhib—addition of nitrification inhibitor.

Split—split fertilization, dividing fertilizer applications into three smaller increments.

Red70—reduction of nitrogen-based fertilizer to 70 percent of baseline.

Red80—reduction of nitrogen-based fertilizer to 80 percent of baseline.

Red90—reduction of nitrogen-based fertilizer to 90 percent of baseline.

NT—conversion from conventional tillage to no-till.

soil inputs and, hence, reduced soil carbon. Observations show that soil carbon levels are sensitive to changes in crop residue inputs (e.g., Peterson et al. [1998]); however, the degree to which a particular soil responds to changes in crop residue inputs depends on many factors, such as the history of land-use management. The soil carbon reduction offsets the reduced N₂O emissions to varying degrees. The net emissions for the three different fertilizer reduction amounts (10, 20, and 30 percent) are similar. This suggests that, at the global scale, the amount of soil carbon lost and the amount of N₂O reduced respond roughly linearly and equally to fertilizer inputs.

An additional consideration regarding potential trade-offs between N₂O emissions and soil carbon is that N₂O reductions are long lasting, whereas soil carbon accumulation is reversible through future changes in management. The reversibility of soil carbon accumulation is not accounted for in this analysis, because all changes in management are assumed to occur immediately and continuously through to 2020.

The nitrification inhibitor leads to the largest reduction in net emissions because it directly decreases emissions from nitrification. Split fertilization also leads to significant net reductions, but it is possible that the DAYCENT simulation is underestimating the mitigation potential of this option. This is because the three separate fertilizer applications are occurring on the same day, regardless of the timing and amount of rainfall represented in the model. If heavy rains happen to fall a couple of weeks after the second fertilizer application, N₂O may be higher than if all of the fertilizer were applied when the crop was planted.

No-till cultivation leads to a large reduction in net emissions primarily because of increased carbon storage in soil and surface residue, although this option also decreases N₂O by a small amount at the

global scale. However, DAYCENT does project higher N₂O emissions under no till for certain locations, which is consistent with data showing higher N₂O emissions under no till, particularly in humid environments (Smith and Conen, 2004). Because the majority of the reduced greenhouse gas emissions from the no-till option are from carbon storage, it should be noted that this benefit is transitory, because the capacity of soils to store carbon is finite and most soils are likely to reach equilibrium within approximately 50 years of land management change. Also, if cultivation intensity is increased in the future, then much of the carbon that was stored is likely to be respired and returned to the atmosphere. However, the reduced N₂O emissions associated with applying nitrification inhibitors and split fertilizer are irreversible and likely to persist indefinitely.

To estimate the breakeven \$/tCO₂e of these mitigation options, DAYCENT results for the change (from baseline) in net emissions, yields, and fertilizer applications are used in combination with crop and fertilizer price information, as well as assumptions about other input costs and labor changes. The change in crop revenue is estimated with DAYCENT changes in yields and IFPRI's current and projected region-specific baseline prices for wheat, maize, and soybeans. Likewise, IFPRI price information for change in fertilizer costs is used. Appendix T provides details on IFPRI's commodity prices.

No capital costs are assumed for any cropland mitigation options.⁷ The nitrification inhibitor option is assumed to incur an additional input cost of \$20 per hectare (Scharf et al., 2005), which is scaled from the United States to other regions. Only two of the options are assumed to incur labor changes. Split fertilization is assumed to require an increase in labor and no till a decrease in labor.⁸ These percentage changes in labor are assumed to be uniform across regions; however, data from the Global Trade Analysis Project (GTAP, 2005) database are used to calculate the share of output attributable to labor costs by crop for each region. This share is used to calculate baseline labor costs per hectare from the estimated value of output per hectare by crop and by region. Labor rates are taken from IFPRI's IMPACT model to calculate the implied number of labor hours per hectare consistent with the labor cost per hectare, as a validity check on the labor costs being estimated. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.2 Rice (CH₄, N₂O, and Soil Carbon)

V.2.2.1 Rice CH₄, N₂O, and Carbon Emissions Characterization

Most rice in Asia and the rest of the world is grown in flooded paddy fields (less than 10 percent of the rice in Asia is grown in upland conditions). When fields are flooded, decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions

⁷ No-till options would require purchasing no-till equipment for direct planting. However, if this equipment is purchased in place of equipment used for traditional tillage, there may be little incremental capital costs associated with no till. Some crop budgets actually indicate lower capital costs for no till because of the need for fewer passes over the field, which leads to reduced equipment depreciation. Thus, no incremental capital costs for the no-till option are assumed.

⁸ Split fertilization is assumed to require 14 percent more labor, assuming one additional pass over the fields, where, for this purpose, seven passes per year are assumed in the baseline (i.e., for tilling, planting, fertilizing, applying herbicide, applying pesticide, and harvesting, some of which may not be done on all fields but may require more than one pass on some farms). The biophysical modeling in DAYCENT assumes a one-time fertilizer application in the baseline and two applications with split fertilization. No till is assumed to decrease labor requirements based on a U.S. Department of Agriculture (USDA) Agricultural Resource Management Survey (ARMS) survey, which provides labor estimates for conventional and conservation tillage on both irrigated and rain-fed land by major crop.

in the soil to develop. Anaerobic decomposition of soil organic matter by methanogenic bacteria generates CH₄. Varying amounts up to 90 percent of the CH₄ is oxidized by aerobic methanotrophic bacteria in the soil (Krüger et al., 2002; Holzapfel-Pschorn et al., 1985; Sass et al., 1990). Some of the CH₄ is also leached away as dissolved CH₄ in floodwater that percolates from the field. The remaining unoxidized CH₄ is transported from the soil to the atmosphere, primarily through the rice plants themselves. Minor amounts of CH₄ also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is therefore one of the most important factors affecting CH₄ emissions. The amount of available carbon susceptible to decomposition is also critical. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH₄ emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH₄ to oxidize but also inhibits further CH₄ production in soils.

Field measurements in China indicate, however, that midseason drainage, while significantly reducing CH₄, actually increases N₂O emissions (Zheng et al., 1997, 2000; Cai et al., 1999). One of the key processes controlling CH₄ and N₂O production/consumption in paddy soils is the reduction potential (Eh) dynamics. Methane and N₂O are produced during different stages of soil redox potential fluctuations.

In addition to water management, other practices (e.g., tillage, fertilization, manure amendments) will alter the soil environmental conditions (e.g., temperature, moisture, pH) and hence affect the soil carbon- and nitrogen-driving processes such as decomposition, nitrification, and denitrification. The changes in the soil biogeochemical processes will finally affect the availability of soil nitrogen and water to the crops and hence alter the crop yields. Because crop residue is the major source of soil organic carbon, the change in crop yield and litter will redefine the soil organic-matter balance, which is one of the most important factors determining the CH₄, soil CO₂, and N₂O emissions (Li et al., 2006).

Soil temperature is also known to be an important factor regulating the activity of methanogenic bacteria and, therefore, the rate of CH₄ production.

V.2.2.2 DNDC Baseline Estimates of Rice CH₄, N₂O, Soil Carbon, and Yields

The DNDC model, in particular the paddy-rice version of the model (DNDC 8.6; Li et al., 2004; Li et al., 2002; Cai et al., 2003; Zhang et al., 2002), was used to estimate baseline and mitigation scenario emissions of CH₄, N₂O, and soil carbon, as well as yield and water resource changes, for Asian rice systems. Greenhouse gas emissions from non-Asian rice systems, which represent about 10 percent of the world's total rice area (Wassmann et al., 2000), are excluded, primarily because data for these areas were not available at the time of the DNDC modeling. The DNDC model and emissions baseline methodologies are briefly described here, and further details are provided in Appendix R. Appendix S summarizes differences between the baseline rice GHG emissions used in this analysis and USEPA (2006).

DNDC is a soil biogeochemical model that simulates both aerobic and anaerobic soil conditions and estimates crop yields based on a detailed crop physiology-phenology model. It is designed for assessing the impact of different management strategies on short-term and long-term soil organic carbon dynamics and emissions of CH₄, N₂O, nitric oxide (NO), and NH₃ from both upland and wetland agricultural ecosystems. DNDC requires data on soils (e.g., pH, soil carbon, bulk density, and soil texture), rice cropping areas and systems (e.g., single rice, double rice, rice rotated with upland crops), climate, and management practices (e.g., fertilizer use, planting and harvesting dates, tillage, water use). DNDC runs

on a daily time step and can therefore capture temporal, as well as spatial, heterogeneity in emissions processes.

DNDC has been tested against several CH₄ and N₂O flux data sets for wetland rice systems in different regions of the world, and overall results indicate that DNDC is capable of estimating the seasonal patterns and magnitudes of CH₄ and N₂O fluxes. In some cases (less than 20 percent of the sites tested), there were discrepancies between modeled and observed patterns of CH₄ and N₂O fluxes. In these cases, minor modifications to capture unique local management conditions, rice varieties, and anaerobic processes resulted in good estimates of greenhouse gas emissions from all rice systems tested (Li et al., 2006; Cai et al., 2003; Zhang et al., 2002; see also Appendix R).

DNDC simulates rice growth and yield by tracking heat (i.e., daily temperature) accumulation, water availability, and nitrogen availability. If there is any stress in heat, water, or nitrogen detected by DNDC, the yield will be reduced accordingly. The impacts of farming practices on yield are modeled based on the effects of the practices on water and nitrogen (it is assumed the practices have little effect on heat flux).

China is the core focus of the rice component of this study because China contains roughly 20 percent of the world's rice paddies and generates 31 percent of the world's rice production (FAOSTAT, 2004a); furthermore, previous DNDC modeling efforts had already collected a detailed database for Chinese rice systems at the county scale. This Chinese rice component of the analysis is described in Li et al. (2006) and briefly summarized here.

Table 1-3 contains DNDC estimates of rice emissions for China, individual water basin regions within China, and other Asian countries (see Section V.1.3.3 for additional baseline summary information). Methane emissions tend to increase over time because of soil carbon accumulation. N₂O emissions tend to decline, also because of the soil carbon accumulation, coupled with an assumed constant rate of fertilization (which increases total denitrification).

Data on rice cropping systems, soils, climate, water management, residue management, fertilizer, and optimum yield profiles are incorporated into DNDC for each of the approximately 2,500 Chinese counties. County data are aggregated to water basin regions within China. Maximum and minimum values of soil texture, pH, bulk density, and soil organic carbon content are derived for each county. These factors are used to determine the most sensitive factors to estimate uncertainty in emissions estimates within each county. Based on sensitivity tests (Li et al., 2004), the most sensitive factors for CH₄ and N₂O emissions from rice paddies are soil texture and soil organic carbon. By varying soil texture and soil organic carbon over the ranges reported in the county-scale database, a range of CH₄ and N₂O emissions for each cropping system in each county is estimated. All emissions estimates from DNDC in this study represent the midpoints of those ranges.

There are 11 different crop rotations, including single rice, double rice, rice-winter wheat, rice-rapeseed, and rice-rice-vegetable. The area occupied by each rotation in each county is quantified by combining the county-scale statistical database of crop-sown areas with a Landsat land-cover map for mainland China (Frolking et al., 2002). Total rice area is assumed to remain fixed over the 2000 to 2020 period under both baseline and mitigation scenarios, though regional changes in rice area are certainly expected to occur; the subject of changing rice area in response to implementing the mitigation options is discussed in Section V.1.3.6.

Table 1-3: Rice-Only Baseline CH₄, N₂O, and Soil Carbon Estimates for 2000, 2010, and 2020 by Asian Region (Midpoints from DNDC in MtCO₂eq/yr; Negative Carbon Numbers Indicate Net Sequestration)

Region	2000			2010 ^a			2020 ^b		
	CH ₄	N ₂ O	Soil Carbon	CH ₄	N ₂ O	Soil Carbon	CH ₄	N ₂ O	Soil Carbon
China	211	199	-25	217	132	-48	223	114	-35
Huaihe	41	23	-4	43	18	-6	44	15	-4
Haihe	3	2	-1	3	1	-1	4	1	-0
Huanghe	2	1	-1	2	1	-0	2	1	-0
Changjian	87	104	-18	90	65	-24	92	56	-18
Songliao	23	8	6	24	6	-2	24	6	-1
Inland	1	0	-0	1	0	-0	1	0	-0
Southwest	1	2	1	1	1	-1	1	1	-0
ZhuJiang	33	38	-2	34	25	-10	35	21	-8
Southeast	19	20	-6	20	15	-5	20	13	-4
Bangladesh	41	4	13	45	2	-1	47	2	-2
India	103	5	19	111	10	-9	117	15	-10
Indonesia ^c	131	36	257	139	5	78	150	4	65
Philippines	58	7	36	60	2	7	64	2	6
Thailand	66	6	70	69	3	14	73	3	12
Vietnam	45	6	40	73	3	7	80	3	6

^a Average of 2006–2010.^b Average of 2016–2020.^c Indonesia has exceptionally large baseline decreases in soil carbon because it is starting from a very high initial soil carbon content (about 7 percent).

Total emissions are estimated from total sown area, including all rice systems that capture more than one rice crop (i.e., double rice) for multiple growing seasons over the course of a year. Rice yields in DNDC, however, are estimated from single-rice systems only and are assumed to be representative of other types of rice systems (i.e., double rice and rice-winter wheat).⁹

Daily weather data (i.e., maximum and minimum air temperatures and precipitation) for 1990 from 610 weather stations in China were acquired from the National Center for Atmospheric Research (<http://dss.ucar.edu/datasets/ds485.0/>). Climate data for 1990 are used for baseline and mitigation scenarios; thus, as with the DAYCENT modeling runs, there is no explicit assumption about anthropogenic climate change out to 2020. Climate, biophysical, and management conditions are assumed to be the same within each county but vary across counties.

Midseason drainage is assumed to be a baseline management practice for a fixed percentage (80 percent) of Chinese paddies currently and out to 2020; the remaining 20 percent is assumed to be under continuous flooding. Shen et al. (1998) estimate that 80 percent of Chinese rice systems have made the

⁹ There are plans to modify the DNDC model so that yields for multiple types of rice cropping systems, in addition to single-rice systems, can be tracked separately.

conversion from continuous flooding to midseason drainage, a practice that decreases CH₄ emissions because it decreases the period over which anaerobic conditions occur. Under midseason drainage, three drainage events are assumed to be carried out for each rice-growing season.

Optimal Chinese rice yields in DNDC were set to increase by 1 percent per year over the 2000 to 2020 period to match yield projections from IFPRI's IMPACT model. As a result, realized yields in DNDC do increase over time but fall short of the prescribed optimal yields due to nutrient limitations, primarily insufficient nitrogen availability.

Fertilizer applications are assumed to be 140 kgN/hectare (70 kgN of urea and 70 kgN of ammonium bicarbonate) for each rice-growing season. These rates remain fixed over the 2000 to 2020 period. Rice straw (1,000 kg-C) is also amended at the beginning of each rice-growing season. No manure is applied.

Less detailed DNDC analyses are carried out for other Asian regions. These emissions analyses are not intended to serve as national inventory studies but rather to provide a basis from which to assess the effects of the different mitigation options. DNDC is run for individual sites under both rain-fed and irrigated conditions in Bangladesh, India, Indonesia, Japan, the Philippines, Thailand, and Vietnam. For each site, soil and climate data were compiled from several sources (Global Soil Data Task Group, 2000; Kistler et al., 2001; Webb et al., 2000). To estimate national-level emissions, the simplified assumption is made that the site-level conditions are representative of the entire country. Therefore, net emissions (CH₄, N₂O, soil carbon) rates per hectare from these test sites are multiplied by the number of hectares under either irrigated or rain-fed conditions in each country, according to data from the International Rice Research Institute (IRRI). These areas also remain fixed over the 2000 to 2020 period. Like the DNDC simulations in China, optimal yield projections out to 2020 from IFPRI (see Appendix R) are used to allow annual baseline yields in DNDC to increase at different rates in different countries.

Midseason drainage is currently not widely practiced outside of China; for this reason, the dominant baseline management condition assumed in these other Asian regions is continuous flooding under either irrigated or rain-fed conditions. Fertilization types and rates are assumed to be the same as in China. DNDC simulations were not carried out for Malaysia, Myanmar, South Korea, and other Southeast Asian countries, but nationally averaged emissions and yield results from DNDC in neighboring regions are used as proxies (see Appendix R).

V.2.2.3 Mitigation Options for Rice CH₄, N₂O, and Soil Carbon Emissions

The mitigation options chosen for rice emissions have been identified as viable options in the literature (e.g., Wassmann et al. [2000]; Van der Gon et al. [2001]). Table 1-4 lists these mitigation options, which include changes in water management that reduce the time over which flooding conditions occur (to reduce anaerobic conditions), use of alternative fertilizers and changes in the timing of organic amendments (to inhibit methanogenesis), or switching from flooded to upland rice to eliminate anaerobic conditions.

Unlike China, most other Asian countries have larger fractions of rice areas under rain-fed management conditions. Mitigation options requiring a change in water management are not simulated on rain-fed areas because these systems are water limited and rely only on precipitation. Mitigation options involving fertilizer management and conversion to upland rice are assessed on all rice areas.

All mitigation options are intended primarily to reduce baseline CH₄ emissions, but N₂O emissions and soil carbon are affected as well. Emissions reductions represented in the final cost estimates represent these net greenhouse gas effects. The mitigation options are simulated by DNDC, and resulting rice crop yields and emissions effects are compared with the DNDC baseline, as described above. Although all

Table 1-4: Rice CH₄, N₂O, and Soil Carbon Mitigation Options Run Through DNDC

Mitigation Option	Description	Greenhouse Gas Effects
Full midseason drainage	In China, shift from 80 percent to 100 percent adoption of midseason drainage. In rest of Asia, conversion from 0 percent to 100 percent. Rice fields are dried three times within a growing season and surface water layer is 5 to 10 cm for remaining, flooded period. Not applied on rain-fed areas.	CH ₄ , N ₂ O, soil carbon
Shallow flooding	Assumes rice paddies are marginally covered by flood water, with the water table fluctuating 5 to 10 cm above and below soil surface. Not applied on rain-fed areas.	Same
Off-season straw	Shifting straw amendment from in-season to off-season can reduce availability of dissolved organic carbon and; thus, methanogens. Assumes rice straw is applied 2 months before rather than at beginning of rice-growing season.	Same
Ammonium sulfate	Baseline fertilizers, urea, and ammonium bicarbonate, replaced with 140 kg/hectare of ammonium sulfate. Sulfate additions to soil can elevate reduction potential, which suppresses CH ₄ production.	Same
Slow-release fertilizer	Nitrogen is slowly released from coated or tablet fertilizer over a 30-day period following application. Applied in the same amount and at the same time as in baseline case. Increases fertilizer-use efficiency.	Same
Upland rice	Assumes upland rice replaces existing paddy rice areas and that fields do not receive any flood water.	Same

mitigation options are represented in the final MACs, DNDC simulates only one mitigation option at a time, assuming that each mitigation option is implemented on all rice lands in 2000 and continuously until 2020. No mitigation options are implemented simultaneously on the same rice lands or on different portions of the rice lands within DNDC.

Unlike the options with DAYCENT, no options that were found to increase net emissions relative to baseline are removed from the rice portion of the analysis, because these net emissions increases were generally small or temporary (i.e., occurring only in the later years of the analysis).

V.2.2.4 DNDC Estimates for Changes in Rice CH₄, N₂O, Soil Carbon, and Yields

Results here provide the most detail for China because that is the country for which the most detailed DNDC modeling runs were carried out. Table 1-5 provides net greenhouse gas results aggregated to the Chinese national level for the baseline and mitigation scenarios, averaged over the entire 2000 to 2020 period. The midpoint estimates from DNDC are those carried forward in the MAC calculations.

Table 1-5: DNDC Estimates of Net Greenhouse Gas Results for Baseline and Mitigation Scenarios for China (Annual Averages in MtCO₂eq/yr over 2000–2020)

Estimate	Baseline	Midseason Drainage	Shallow Flooding	Off-Season Straw	Ammonium Sulfate	Slow-Release Fertilizer	Upland Rice
Midpoint ^a	315	296	140	298	235	326	41
High estimate	484	445	232	468	379	454	71
Low estimate	146	148	47	128	90	199	11

Source: Li et al., 2006.

^a The high, mid, and low estimates are the results of most sensitive factor (MSF) estimates carried out with the DNDC model.

Table 1-6 shows individual greenhouse gas changes from the baseline, as well as the net greenhouse gas and yield changes, at the Chinese national level on a per-hectare basis; change in water-use requirements are also shown but are not used in the final cost estimates because water is not a priced commodity in these rice systems.

Table 1-6: Changes from Baseline in Greenhouse Gas Emissions, Crop Yields, and Water Consumption for China (Annual Averages over 2000–2020; Negative Numbers Indicate Decreases Relative to the Baseline)

Management Option	CH ₄ (kgCO ₂ eq/ha)	N ₂ O (kgCO ₂ eq/ha)	CO ₂ (kgCO ₂ /ha)	Net Greenhouse Gas (kgCO ₂ eq/ha)	Yield (kg C/ha)	Water (mm/yr)
Midseason drainage	–2,411	1,283	–1	–1,129	81	–9
Shallow flooding	–7,402	–2,440	591	–9,251	134	–248
Off-season straw	–663	–40	21	–682	43	0
Ammonium sulfate	–367	–3,668	–85	–4,120	28	0
Slow-release fertilizer	287	727	–191	823	131	0
Upland rice	–11,794	–3,018	239	–14,573	–381	–566

Source: Li et al., 2006.

As described in Li et al. (2006), despite large-scale adoption of midseason drainage, there is still large technical potential for additional CH₄ reductions from Chinese rice paddies (e.g., over 60 percent reductions are achieved in the shallow flooding scenario over 2000 to 2020). However, management changes that reduce CH₄ emissions simultaneously affect N₂O emissions and soil carbon dynamics such that the net greenhouse gas effects should be considered. Midseason drainage, for example, is an effective CH₄ reduction strategy but can significantly increase N₂O emissions. Ammonium sulfate reduces CH₄ by a small amount but significantly reduces N₂O; these low CH₄ reductions are largely due to the fact that mid-season drainage rather than continuous flooding is the baseline practice (conditions under which sulfate is less effective at reducing CH₄), whereas more significant N₂O reductions occur because ammonium sulfate is less susceptible to volatilization than the urea it is replacing (because all of the nitrogen is already in the ammonium form).

In terms of net greenhouse gas technical mitigation potential only, the most effective mitigation option appears to be shallow flooding, followed by ammonium sulfate, full midseason drainage adoption, and off-season straw amendments; the slow-release fertilizer scenario enhances soil carbon but increases the other gases and thus does not reduce net greenhouse gas emissions compared with the baseline. The upland rice scenario, where it is assumed that existing rice fields receive no flood water, is simulated in DNDC for China and is found to decrease net greenhouse gas emissions by about 87 percent.

The relative order of mitigation across scenarios remains the same even when the proportions of midseason drainage vary (Li and Salas, 2005), suggesting that these results may apply to other regions where midseason drainage has not been widely adopted. Appendix R contains information about the time dynamics of these net greenhouse gas changes for each scenario for 2000 to 2020.

Most mitigation options, including slow-release fertilizer, increase rice yields compared with the baseline. In general, rice yields vary directly with nitrogen availability, assuming no heat stress and sufficient water resources: higher nitrogen availability leads to higher yields. Relative to continuous flooding, midseason drainage or shallow flooding elevates soil aeration and hence accelerates decomposition, which produces more inorganic nitrogen and increases nitrogen availability. Slow-release

fertilizer improves the fertilizer use efficiency by extending the period of nitrogen availability for the plants, effectively increasing total nitrogen availability. Similar to the slow-release fertilizer, ammonium sulfate has relatively low solubility compared with baseline fertilizer, urea, and ammonium bicarbonate and thus is less susceptible to leaching. Although theoretically off-season straw may not have a direct effect on yield, it is assumed that early incorporation of straw favored its decomposition because of the high reduction potential conditions before flooding. This higher decomposition rate enhanced yields caused by increased soil nitrogen availability when the rice was transplanted. The yield difference between upland rice and paddy rice is in the rice's genetic characteristics. The current upland rice has genetically low yield. This situation may change if new strains of upland rice are developed. In summary, management practices that increase nitrogen availability (through increased decomposition or better synchronization with plant needs) will typically increase rice yields.

Shifting to full midseason drainage and shallow flooding are also water-saving practices because they significantly decrease water consumption (i.e., evapotranspiration), whereas the other mitigation options, involving only changes in fertilization or straw amendment, have almost no effect on water consumption.

Table 1-7 shows net greenhouse gas results under each mitigation option compared with the baseline for the other Asian countries. The pattern of results observed in China is similar for these other countries. The most effective mitigation options in terms of net greenhouse gas reductions involve a change in water management; the options involving a change in fertilization management are less effective. Slow-release fertilizer is also a particularly poor greenhouse gas reduction strategy in these other Asian countries, often leading to no net greenhouse gas reductions compared with the baseline.

Table 1-7: Net Greenhouse Gas Results for Baseline and Mitigation Options for Other Asian Countries (Annual Averages in MtCO₂eq/yr over 2000–2020)

Country	Baseline	Midseason Drainage	Shallow Flooding	Off-Season Straw	Ammonium Sulfate	Slow-Release Fertilizer	Upland Rice
Bangladesh	47	23	8	32	43	47	21
India	113	60	23	79	101	115	41
Indonesia	237	139	142	193	223	238	190
Japan	29	15	6	22	26	29	10
Philippines	72	40	16	54	65	73	26
Thailand	91	79	74	65	85	91	72
Vietnam	84	71	59	51	78	84	43

To estimate the breakeven \$/tCO₂eq of these mitigation options, DNDC results for the change from baseline in net emissions, yields, and fertilizer applications are used in combination with rice crop and fertilizer price information, as well as assumptions about other input costs and labor changes. Change in crop revenue is estimated with DNDC changes in yields and IFPRI's changes in current and projected region-specific baseline producer prices for rice (see Appendix T). For the ammonium sulfate option, the additional input cost is the extra cost of ammonium sulfate compared with urea and ammonium bicarbonate, based on FAO prices. For the slow-release fertilizer option, the additional input cost is assumed to be \$20 per hectare for all regions, based on the cost of using Agrotain, a urease inhibitor thought to be an appropriate proxy.

No one-time capital costs are assumed for any of the rice mitigation options. Three of the options (i.e., midseason drainage, shallow flooding under irrigated conditions, and off-season straw amendments) are

assumed to require additional labor compared with baseline practices. The percentage increase in labor for these three options is assumed to be uniform across all regions and is estimated by assuming percentage changes in preharvest labor based on data from Moser and Barrett (2002) for systems of rice intensification as a rough proxy. Preharvest labor is assumed to account for 75 percent of total labor in all regions. GTAP data on value of inputs used in rice production are used to calculate the share of output value attributable to rice labor costs for each region. This share is used to calculate baseline labor costs per hectare from the estimated value of output per hectare by region. Labor rates are taken from IFPRI's IMPACT model to calculate the implied number of labor hours per hectare, consistent with the labor cost per hectare, as a validity check on the labor costs being estimated. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.3 Livestock (CH₄ and N₂O)

V.2.3.1 Livestock Enteric CH₄ Emissions Characterization

Methane is produced as part of the normal digestive process in animals. During digestion, microbes present in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process is referred to as enteric fermentation and produces CH₄ as a by-product, which can be exhaled or eructated by the animal. The amount of CH₄ produced and excreted by an animal depends primarily on the animal's digestive system and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH₄ because of their unique digestive systems. Ruminants possess a rumen, or large fore-stomach, in which microbial fermentation breaks down coarse plant material for digestion. Nonruminant domesticated animals (e.g., swine, horses, mules) also produce CH₄ emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine, where the capacity to produce CH₄ is lower (USEPA, 2005b).

An animal's feed quality and feed intake also affect CH₄ emissions. In general, lower feed quality or higher feed intake lead to higher CH₄ emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types, as well as among different management practices for individual animal types.

Because CH₄ emissions represent an economic loss to the farmer—where feed is converted to CH₄ rather than to product output—viable mitigation options can entail feed efficiency improvements to reduce CH₄ emissions per unit of beef or milk. However, these mitigation options can actually *increase* CH₄ per animal.

V.2.3.2 Livestock Manure CH₄ and N₂O Emissions Characterization

The management of livestock manure can produce both CH₄ and N₂O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced through the nitrification and denitrification of the inorganic nitrogen derived from livestock manure and urine.

When livestock and poultry manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid or slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH₄. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH₄ (USEPA, 2005b).

Ambient temperature and manure storage or residency time also significantly affects the amount of CH₄ produced because of influences on the growth of the bacteria responsible for CH₄ formation. For

example, CH₄ production generally increases with rising temperature and residency storage time (USEPA, 2005b). Also, for nonliquid-based manure systems, moist conditions (which are a function of rainfall and humidity) favor CH₄ production. Although the majority of manure is handled as a solid, producing little CH₄, the general trend in manure management, particularly for large dairy and swine producers in the United States and other industrialized countries, is one of increasing use of liquid systems.

The composition of the manure also affects the amount of CH₄ produced. Manure composition varies by animal type and diet. In general, the greater the energy content of the feed, the greater the potential for CH₄ emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH₄-producing capacity, whereas range cattle fed a low-energy diet of forage material produce manure with about half the CH₄-producing potential (USEPA, 2005b). However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

A small portion of the total nitrogen excreted in manure and urine is expected to convert to N₂O. The production of N₂O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system (USEPA, 2005b). For N₂O emissions to occur, the manure must first be handled aerobically where NH₃ or organic nitrogen is converted to nitrates and nitrites (nitrification) and then handled anaerobically, where the nitrates and nitrites are reduced to nitrogen gas (N₂), with intermediate production of N₂O (i.e., denitrification) (Groffman et al., 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions but that also contain pockets of anaerobic conditions, such as rain events.

V.2.3.3 The USEPA Baseline Estimates of Livestock Enteric CH₄ Emissions

Baseline emissions of and activity data for livestock enteric CH₄ are taken directly from USEPA (2006). Enteric CH₄ emissions from livestock are estimated to be the second largest source of global agricultural non-CO₂. In 2000, global enteric CH₄ emissions were estimated to be 85,648 Gg or 1,799 MtCO₂eq and are projected to increase more than 30 percent by 2020 to 111,633 Gg or 2,344 MtCO₂eq (a 32 percent increase relative to 1990). Livestock enteric CH₄ accounted for 32 percent of global agricultural non-CO₂ emissions in 2000. In the United States, enteric CH₄ accounts for 27 percent of agricultural non-CO₂ and less than 2 percent of all greenhouse gas emissions (USEPA, 2005b).

V.2.3.4 The USEPA Baseline Estimates of Livestock Manure CH₄ and N₂O Emissions

Baseline emissions of and activity data for livestock manure CH₄ and N₂O are taken directly from USEPA (2006). The joint CH₄ and N₂O emissions from livestock manure are estimated to be the fourth largest source of global agricultural non-CO₂ emissions. In 2000, livestock manure emissions were estimated to be 421 MtCO₂eq, or 10,732 Gg of CH₄ and 632 Gg of N₂O, and are projected to increase 24 percent by 2020 to 523 MtCO₂eq, or 12,832 Gg of CH₄ and 818 Gg of N₂O (a 21 percent increase relative to 1990). Livestock manure emissions accounted for less than 8 percent of global agricultural non-CO₂ emissions in 2000. In the United States, joint CH₄ and N₂O emissions from livestock manure account for 13 percent of agricultural non-CO₂ emissions and less than 1 percent of all greenhouse gas emissions (USEPA, 2005b).

V.2.3.5 Mitigation Options for Livestock Emissions

Non-CO₂ greenhouse gas emissions from livestock can be reduced primarily through either reducing CH₄ emissions that occur during the normal digestive process (i.e., enteric fermentation) or capturing

CH₄ emitted by livestock manure. There is also potential to affect N₂O emissions from manure management, either indirectly through options that target CH₄, but also through mitigation options that primarily target N₂O. However, limited quantitative information is available on the co-effects of CH₄ mitigation options on N₂O or the cost or emissions reductions associated with options focused on N₂O. Thus, the focus here is on options designed to reduce CH₄ but to account for changes in N₂O emissions for those options that change livestock populations by assuming a change in N₂O emissions proportionate to the change in livestock population.

V.2.3.5.1 Mitigation Options for Livestock Enteric CH₄

The enteric CH₄ mitigation options fall into four general categories: (1) improvements to food conversion efficiency by increasing energy content and digestibility of feed, (2) increased animal productivity through the use of natural or synthetic compounds that enhance animal growth and/or lactation (e.g., bovine somatotropin [bST], antibiotics), (3) feed supplementation to combat nutrient deficiencies that prevent animals from optimally using the potential energy available in their feed, and (4) changes in herd management (e.g., use of intensive grazing).¹⁰ Some of these proposed options for enteric fermentation may actually *increase* net greenhouse gas emissions per animal but lead to an even larger increase in productivity. Thus, emissions per unit of product (e.g., meat, milk, or work) decline, and mitigation at the national or regional level requires a sufficient reduction in the number of animals to more than offset the increase in emissions per animal. To capture this issue, two separate estimates of mitigation potential and costs were developed assuming both a constant number of animals and constant production. The static, engineering approach does not allow for simultaneous adjustment in both number of animals and production; however, sensitivity experiments at the end of this section using the global agricultural commodity market model, IMPACT, allow for these dynamic feedbacks to occur.

Table 1-8 summarizes the enteric fermentation options. Most of these options could also be applied to other livestock species (e.g., buffalo, sheep, goats), but no data were available on the emissions reductions or productivity effects that would be expected for those species.

V.2.3.5.2 Mitigation Options for Livestock Manure CH₄ and N₂O

All manure CH₄ mitigation options involve the capture and use of CH₄ through anaerobic digesters. Anaerobic digesters are currently in limited use on large-scale livestock operations in developed regions, often primarily as a means of treating and stabilizing waste and controlling odor, but the CH₄ that is captured is also used as an energy source. Small-scale, ambient temperature digesters are also being used in developing regions, such as China, India, and Vietnam, for household energy generation. The feasibility of digesters depends in part on climate. There are a large number of different types of digesters that can be used, with some being more appropriate for certain climates or livestock species than others. Another important characteristic of digester systems is whether they include engines for electricity generation. Systems generating electricity can potentially create savings by offsetting farm purchases of electricity or even selling the electricity. Systems that do not include electricity generation generally use the heat generated for on-farm use to offset purchases of heating fuels.

¹⁰ Emissions can also be mitigated through other methods, such as improving genetic characteristics, feeding compounds that inhibit rumen methane formation, improving reproduction efficiency, and controlling disease better. However, data are currently insufficient to include estimates for these options.

Table 1-8: Livestock Enteric Fermentation Greenhouse Gas Mitigation Options

Mitigation Option	Description	Greenhouse Gas Effects ^a
Improved feed conversion	Increase the amount of grain fed to livestock to increase the proportion of feed energy being converted to milk, meat, or work instead of animal maintenance. This option tends to increase emissions per animal but reduce emissions per unit output. It is more effective in reducing emissions per unit of production in regions where baseline feed is of relatively low quality. This option is applied to both beef and dairy cattle in all regions, although it was excluded from the MACs for some developed regions where it resulted in slightly higher GHG emissions.	CH ₄ , some N ₂ O
Antibiotics	Administer antibiotics (e.g., monensin) to beef cattle to promote faster weight gain, which reduces time to maturity and CH ₄ production per kilogram of weight gain. This option is applied in all regions.	CH ₄ , some N ₂ O
Bovine somatotropin (bST)	Administer bST to dairy cattle to increase milk production. In many cases, this option increases CH ₄ emissions per animal but typically increases milk production sufficiently to lower emissions per kilogram of milk. Because of opposition to the use of bST in many countries, this option was only applied in selected countries that currently approve of the use of bST or are likely to approve its use by 2010.	CH ₄ , some N ₂ O
Propionate precursors	Involves administering propionate precursors to animals on a daily basis. Hydrogen produced in the rumen through fermentation can react to produce either CH ₄ or propionate. By adding propionate precursors to animal feed, more hydrogen is used to produce propionate and less CH ₄ is produced. This option is applied to both beef and dairy cattle in all regions.	CH ₄ , some N ₂ O
Antimethanogen	Vaccine in development by Commonwealth Scientific and Industrial Research Organization (CSIRO) that can be administered to animals and will suppress CH ₄ production in the rumen. This option is applied to beef and dairy cattle, sheep, and goats in all regions.	CH ₄ , some N ₂ O
Intensive grazing	Moving to a more management-intensive grazing system where cattle are frequently rotated between pastures to allow recently grazed pastures time to regrow and to provide cattle with more nutritious pasture grazing that will permit replacement of more feed grains. This option may actually reduce animal yields but will decrease emissions by an even larger percentage. This option is applied to beef and dairy cattle in developed regions and Latin America.	CH ₄ , some N ₂ O

^a For this analysis, effects on N₂O are estimated only for the scenarios where production is held constant and there is a change in livestock population.

The types of digesters are aggregated based on a categorization of representative systems provided by the USEPA's AgStar program (Table 1-9). For most regions, swine and dairy cattle account for the majority of greenhouse gas emissions from manure, largely because their manure is often managed in liquid systems under anaerobic conditions. Although CH₄ emissions from manure could potentially be captured from additional species (e.g., beef cattle, buffalo, sheep, goats), these species typically account for much smaller shares of emissions and are often managed on pasture much of the year with solid manure handling. Manure from livestock on pasture does not produce much CH₄ because it decomposes under aerobic conditions, resulting in little to no emissions. Based on IPCC default factors, the CH₄ emissions factor is actually higher for digesters than for dry manure management systems such as pasture.

Complete-mix, plug-flow, fixed-film, and large-scale covered lagoon digesters are applied only in the United States, EU-15, Japan, Australia, other developed countries, Eastern Europe, Central Asia, FSU, China, South Korea, and other East Asian regions, based on climate, environmental regulations, capital costs, and other considerations. The dome, polyethylene bag, small-scale covered lagoon, and flexible-bag digesters are applied in all other world regions. China and other parts of East Asia are the only regions where digesters in both of these groups are applied. Applicability of these options was further refined by allocating the share of baseline emissions to swine and dairy cattle and applying emissions reductions only to those portions of the emissions stream. The share of livestock manure emissions due to dairy and swine is based on USEPA (2006), which relies on both IPCC inventory default methodologies and individual country greenhouse gas inventory reports.

CH₄ reduction efficiencies are assumed to be 85 percent from baseline for the complete-mix, plug-flow, fixed-film, and large-scale covered lagoon digesters based on the difference between IPCC default emissions factors for anaerobic manure management, where CH₄ is released into the atmosphere, and digesters. For the smaller-scale digesters applied in developing countries, the reduction efficiency is assumed to be 50 percent from baseline, where baseline emissions are much lower because of a different distribution of manure management practices and the likelihood of less efficient CH₄ capture.

Capital costs are taken from the USEPA's AgStar program (Roos, personal communication, 2005), which estimates the capital cost per 1,000 pounds of liveweight. These values are combined with the 1996 IPCC guideline values for average liveweight for different species in regions around the world to generate estimates of the capital cost per animal. Because liveweight per animal tends to be much smaller in developing countries, the capital cost per animal ends up being lower than in developed regions. This cost is annualized assuming that the large-scale digesters have an expected useful lifetime of 20 years and the small-scale digesters have an expected useful lifetime of 10 years.

GTAP data on labor cost shares by region for livestock production and IMPACT data on regional agricultural wage rates are used to calculate the baseline labor hours per animal and change in hours to verify the reasonableness of these assumptions, as described above for cropland soil management and rice cultivation. For large-scale digesters, labor requirements for swine farms are assumed to increase by 2 percent for options without engines and 4 percent for those with engines. For dairy farms, labor requirements are assumed to increase by 0.5 percent for options without engines and 1 percent for those with engines. The percentage increase in labor is smaller, because dairy farming is already much more labor intensive and requires much more labor per animal in the baseline. The increase in labor for dairy farms is calculated by assuming 200 hours per year in the United States for digester operation, repairs, management, and typical farm size of 800 cows with 50 hours of labor per head per year in the baseline. For hog farms, it is again assumed that a digester will add about 200 hours of labor per year, but assuming an average of about 5,000 hogs per farm per year, that assumption could potentially add a

Table 1-9: Livestock Manure Management Greenhouse Gas Mitigation Options

Mitigation Option	Description	Greenhouse Gas Effects ^a
Complete-mix digester	These digesters are more common in warmer climates, where manure is flushed out of barns or pens with water, lowering the solids' concentration to a level generally between 3 percent and 10 percent. Often there is a mixing tank where the manure accumulates before entering the digester. These digesters make use of gravity and pumps to move the manure through the system. They are often in the shape of a vertical cylinder and made of steel or concrete with a gas-tight cover. These digesters are typically heated to maintain a constant temperature and constant gas flow.	CH ₄
Plug-flow digester	These digesters consist of long and relatively narrow heated tanks, often built below ground level, with gas-tight covers. Plug-flow digesters are only used for dairy manure because they require higher manure solids' content, around 11 percent to 13 percent. As with complete-mix digesters, they are maintained at constant temperatures throughout the year to maintain consistent gas production.	CH ₄
Fixed-film digester	This digester option may be appropriate where concentrations of solids are very low, such as in manure management situations where manure is very diluted with water. Fixed-film digesters consist of a tank packed with inert media on which bacteria grow as a biofilm.	CH ₄
Covered lagoon digester, large-scale	Covered earthen lagoons are the simplest of the systems used in developed countries and generally the least expensive, though there is quite a bit of variation in the systems that have been built. This system is used with low manure solids' concentration (less than 3 percent) and can be used for swine or dairy cattle. CH ₄ is captured by covering the lagoon where manure is stored with a floating cover and piping the gas out to a flare or used on-farm. Because these digesters are not generally heated, the available gas flow varies significantly over the course of the year.	CH ₄
Dome digester, cooking fuel and light	These are small-scale, unheated digesters used in some developing nations, including China and India. A typical dome digester is a brick-lined cylinder sunk in the ground with a wall dividing the cylinder in two with inlet and outlet ports connected to the bottom of the tank. Biogas generated is typically used by the household for cooking and other household energy needs.	CH ₄
Polyethylene bag digester, cooking fuel and light	This small-scale unheated digester is in use in a variety of developing countries. The digester essentially consists of a hole dug in the ground and covered with a plastic bag, with an area for input of manure and a pipe with a valve for biogas produced. Biogas generated is typically used by the household for cooking and other household energy needs.	CH ₄
Covered lagoon, small-scale, for cooking fuel, light, shaft power	This is smaller-scale and much cheaper version of the covered lagoon above, used to generate biogas for household use. Some of these digesters may produce enough energy for shaft power, in addition to household cooking and other uses.	CH ₄
Flexible-bag digester, cooking fuel and light	This is another relatively simple and low-cost unheated digester used in developing countries where the biogas is generated and collected within a plastic bag.	CH ₄

^a Unlike options for reducing emissions from enteric fermentation, none of the options included for manure management are expected to affect yields and there are no effects on N₂O currently being estimated.

digester and about 2 hours of labor per hog annually in the baseline. Options with engines and accompanying electricity generation and transfer equipment were assumed to require twice as much labor as those that produce heat only. For the small-scale digesters in developing nations, labor was assumed to increase by 2.5 percent for options without engines and 5 percent for those with engines that rely on manure from either swine or dairy cattle. Many of these digesters are used on operations with only a few animals and often combine manure from multiple species with other household wastes.

None of these manure management options are expected to change livestock yields. Revenues (or cost savings) are generated from using captured CH₄ (essentially natural gas) for either heat or electricity on the farm. Revenues are scaled for other non-U.S. regions based on a U.S. Energy Information Agency (USEIA) electricity price index (2003).

Breakeven prices (\$/tCO₂eq) for these mitigation options are calculated by region and by species using the emissions reductions from baseline, annualized capital costs, changes in labor costs, and energy savings or revenue. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.3.6 Changes in Livestock CH₄ and Productivity

Figure 1-3 shows total livestock emissions (enteric fermentation and manure management) associated with the baseline and mitigation scenarios, assuming a constant number of animals, where each option is assumed to be applied to 100 percent of the appropriate livestock species (see Tables 1-8 and 1-9), and appropriate regions. Similarly, Figure 1-4 shows the relative emissions under baseline and the mitigation scenarios, assuming constant production. Because percentage emissions reductions are assumed to be the same across all large-scale digesters and across all small-scale digesters, the individual manure management mitigation options identified in Table 1-9 are aggregated here.

Figure 1-3: Global Net Greenhouse Gas (CH₄ and N₂O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Number of Animals Constant

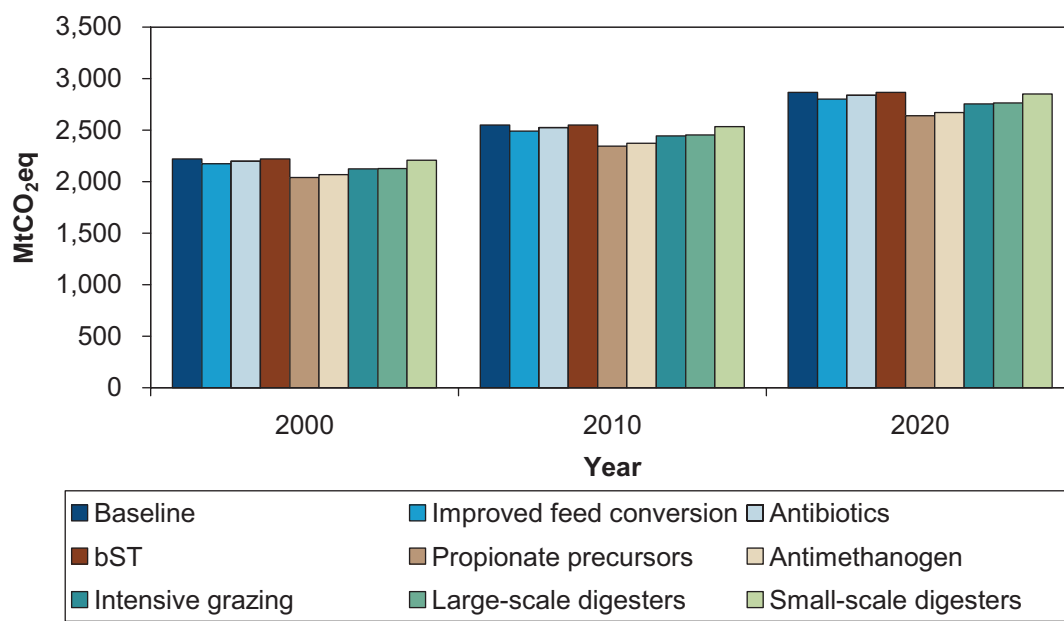
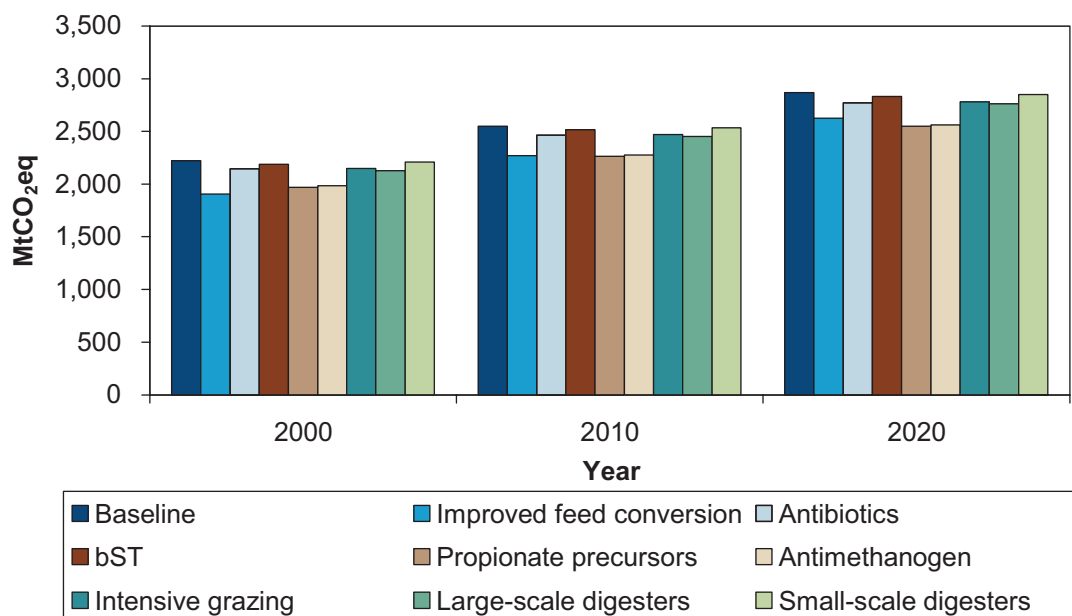


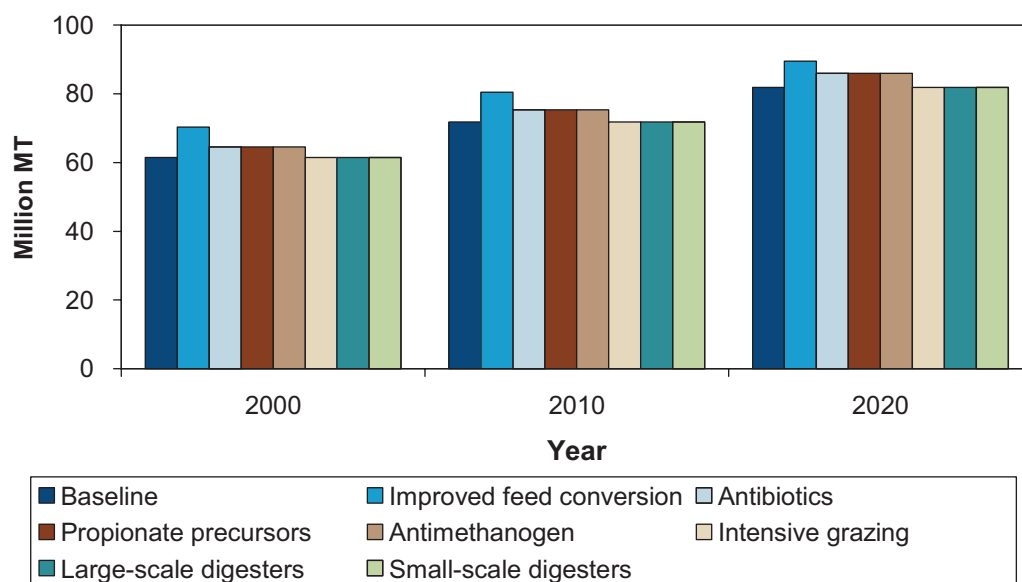
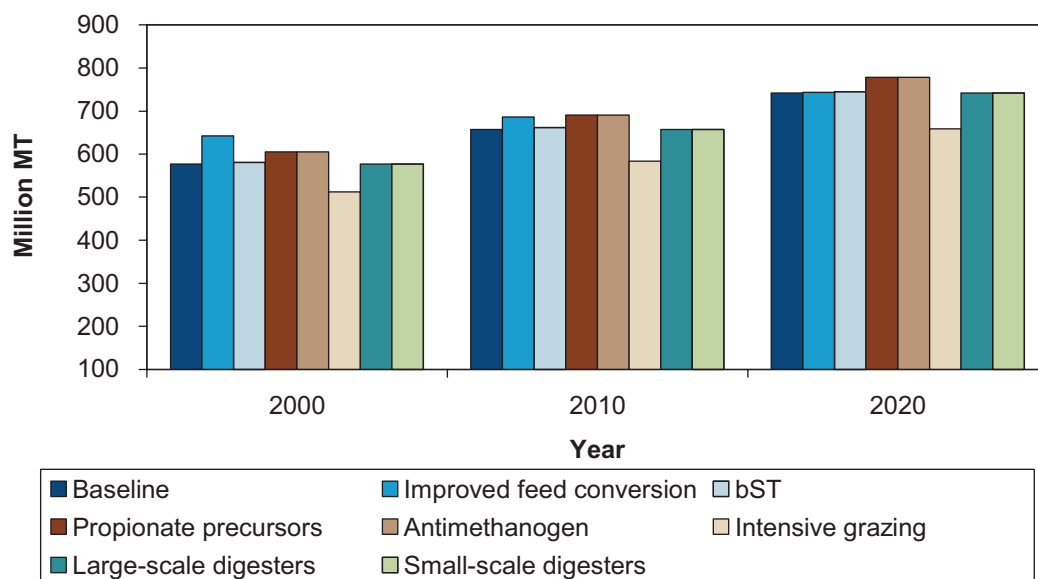
Figure 1-4: Global Net Greenhouse Gas (CH₄ and N₂O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Production Constant



Because some of the enteric fermentation options increase yields in many regions, holding production of meat and milk constant means that there will be fewer animals needed for production. Thus, emissions tend to fall more under the constant production assumption than the constant animals assumption. For instance, improved feed conversion has such large positive yield impacts that emissions under full adoption of that option are about 250 MtCO₂eq less annually when holding production constant and reducing the number of livestock, than when the number of animals is held constant. Section V.1.3.6 presents results that reflect adjustments for market impacts where there are simultaneous changes in the number of animals and in production. In practice, a combination of mitigation options would be adopted and no single option would be adopted for all production. In Section V.1.3.4, MACs are presented that assume partial adoption of each of the available options in each region. However, Figures 1-3 and 1-4 are included to give a sense of the relative emissions that would occur under different production scenarios.

Holding the number of animals constant, emissions are lowest under intensive grazing, followed by propionate precursors, antimethanogen, large-scale digesters, improved feed conversion, small-scale digesters, antibiotics, and bST. However, when production is held constant, the order differs, with improved feed conversion followed by propionate precursors, antimethanogen, intensive grazing, large-scale digesters, antibiotics, small-scale digesters, and bST.

As mentioned above, an important component of these options that will influence net emissions is the change in yield corresponding to each of these options. For some options (e.g., improved feed conversion), the yield effects vary substantially across regions because of widely differing baseline conditions. To summarize the primary overall yield effects, Figures 1-5 and 1-6 show the difference in global production of beef and milk from dairy cattle under full adoption of each of these options, holding the number of animals constant.

Figure 1-5: Global Beef Production under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant**Figure 1-6: Global Production of Milk from Dairy Cattle under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant**

For both beef and milk from dairy cattle, the largest yield increases are for improved feed conversion in 2000. Yield increases relative to baseline are smaller in future years, largely because productivity is improving rapidly under the baseline.¹¹ Improved feed conversion remains the option with the largest average global yield improvement for beef production in all years. Antibiotics, propionate precursors, and antimethanogen all increase beef yield by a similar amount, while intensive grazing, large-scale digesters, and small-scale digesters are assumed to have no impact on beef yield. For milk yield, propionate precursors and antimethanogen lead to similar increases in yield, which become greater than improved feed conversion by 2010. The use of bST leads to a small increase in yield, which would be larger were it not for assumptions that many regions will not adopt this option. Large-scale and small-scale digesters are assumed to have no impact on milk yield. Intensive grazing has a negative effect on milk yield.

¹¹ The percentage increase in yield attributable to the mitigation option for improved feed conversion is calculated for each year by netting out the percentage increase in baseline yield projected by IMPACT. This is done to reflect improved practices expected to be adopted in the baseline and avoid double-counting improvements in yield.

V.3 Results

V.3.1 Estimating Average Costs and Constructing Abatement Curves

The methods used to estimate the average cost of each mitigation option and construct the MACs in the agricultural sector follow the general methodology described in Section I. This section shows additional baseline emissions data (as described in Section V.1.2), the average costs of the mitigation options for key countries, and the MACs for key countries and world totals.

The average cost for each mitigation option represents the present-value breakeven price, expressed as 2000\$ t/CO₂eq, where total benefits equal total costs. The \$/tCO₂eq is estimated according to

$$\sum_{t=1}^T \left[\frac{(P \times ER)(1 - TR) + R(1 - TR) + TB}{(1 + DR)^t} \right] = CC_0 + \sum_{t=1}^T \left[\frac{RC(1 - TR)}{(1 + DR)^t} \right] \quad (1.1)$$

where

- P = The breakeven price of the option in dollars per metric ton of CO₂ equivalent (\$/tCO₂eq).
- ER = The emissions reduction achieved by the technology (MtCO₂eq).
- R = The revenue generated from energy production (scaled based on regional energy prices) or change in agricultural commodity prices (\$).
- T = The option lifetime (years).
- DR = The selected discount rate (10%).
- CC = The one-time capital cost of the option (\$).
- RC = The recurring (operation and maintenance [O&M]) cost of the option (portions of which may be scaled based on regional labor costs) (\$/year).
- TR = The tax rate (40%).
- TB = The tax break equal to the capital cost divided by the option lifetime, multiplied by the tax rate (\$).

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

$$P = \frac{CC}{(1 - TR)ER \sum_{t=1}^T \frac{1}{(1 + DR)^t}} + \frac{RC}{ER} - \frac{R}{ER} - \frac{CC}{ER \cdot T} \cdot \frac{TR}{(1 - TR)} \quad (1.2)$$

The cost estimate takes into account greenhouse gas reductions, revenue effects (e.g., positive or negative changes in yield), any required capital costs (e.g., anaerobic digesters), labor requirements, and changes in other input costs (e.g., increase or decrease in fertilizer applications), all relative to baseline conditions. Section V.1.2 above describes the individual mitigation options; the methods for estimating their associated effects on greenhouse gas emissions and yields; and the assumptions used for other input, capital, and labor costs.

MACs showing greenhouse gas reductions, in terms of percentage reductions from the baseline in 2010 and 2020, are estimated for key regions and world totals. Emphasis is placed on percentage reductions from the baseline, rather than on absolute emissions reduction numbers, because the overall

trends are most important to convey for this analysis. Furthermore, the baselines for croplands and rice cultivation are not comprehensive greenhouse gas inventory estimates so that the percentage changes from these baselines are viewed as more transferable to other kinds of analyses.

To construct the MAC, lines are essentially drawn to connect the points representing the average cost of each mitigation option (where the X axis is MtCeq mitigated and the Y axis is \$/tCO₂eq). The following general factors are estimated to ensure the MAC can represent simultaneous adoption of all mitigation options. First, a technical applicability fraction is estimated to ensure the mitigation option is applied only to the correct portion of baseline emissions. For example, options to reduce dairy cattle emissions can only be applied to the fraction of livestock emissions attributable to dairy cattle. Second, an implied adoption rate is estimated by segmenting the applicable baseline emissions into uniform fractions based on the number of mitigation options. For example, if 10 mitigation options could technically be applied to reduce cropland N₂O emissions, then each mitigation option is assumed to apply to only 10 percent of baseline emissions. This is a simplistic method to avoid double counting among mitigation options, but unfortunately it does not allow lower-cost options to out-compete higher-cost options. Other factors in addition to cost (e.g., adoption feasibility and implementation barriers) can of course determine the extent to which one mitigation option is adopted over another. Because such factors are not included, this static approach of allowing each mitigation option to be applied equally is viewed as a conservative approach to estimate the technical mitigation potential.

All mitigation options are assumed to be implemented immediately (i.e., in the first data year, 2000), but only for appropriate regions, and are assumed to remain in place continuously until 2020. Therefore, the MACs presented in 2010 represent the emissions reductions and associated costs that occur in year 2010, assuming that all mitigation options have been implemented since 2000. The emissions reductions represented in 2010 are estimated relative to the 2010 emissions baseline under the assumption that no mitigation options have been implemented since 2000.

Two general approaches are used to calculate all MACs in the agricultural sector. The first approach keeps cropland area, rice area, and livestock populations constant over time, allowing total production to change as yields per hectare and productivity per animal change as a result of the mitigation options. The biophysical modeling in DAYCENT and DNDC also holds land area constant over time. The second approach holds crop production, rice production, and livestock production (e.g., production of milk and beef) constant over time, allowing land area and animal populations to change (postprocess). In this case, land area is changed for each region by scaling the revised per-hectare yield numbers to maintain the same regional crop or rice production as in the baseline. Livestock population numbers are changed in a similar way. This latter approach is particularly important for the livestock sector, because many proposed enteric fermentation mitigation options actually *increase* CH₄ emissions per animal but decrease CH₄ emissions per unit product. Results are shown for both approaches.

V.3.2 Baselines, Mitigation Costs and MACs for Croplands

Table 1-10 presents the baseline net GHG emissions (N₂O and soil carbon) from croplands management by region by year used in this analysis. These are the values to which all estimated percentage reductions in croplands emissions were applied.

Table 1-10: Baseline Net GHG Emissions from Croplands from DAYCENT Estimates (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	29	32	36
Annex I	508	484	521
Australia/New Zealand	13	17	17
Brazil	27	30	30
China	91	97	104
Eastern Europe	38	39	41
EU-15	91	93	101
India	66	69	73
Japan	0	0	0
Mexico	14	16	28
Non-OECD Annex I	171	123	124
OECD	313	338	373
Russian Federation	171	123	124
South & SE Asia	25	26	28
United States	167	179	200
World Total	839	830	893

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Note: These emissions include only croplands used for wheat, maize, or soybean production.

Note: Combinations of countries included in regions available from DAYCENT are not identical to those included in regions presented in this report, but were aggregated to approximate these regions as closely as possible.

Table 1-11 shows information on the yield effects, emissions reductions, and costs associated with individual croplands mitigation options for the United States, EU-15, Brazil, China, and India.

Table 1-12 provides estimates of the percentage reduction in net GHG emissions (relative to the croplands baseline used in this analysis) that could potentially be achieved at prices between \$0/tCO₂eq and \$60/tCO₂eq for both 2010 and 2020 in major regions around the world.

Figure 1-7 shows the globally aggregated MAC for cropland greenhouse gas mitigation for 2000, 2010, and 2020, in terms of percentage emissions reductions from baseline over the applicable carbon price range. With no price signal (i.e., at \$0/tCO₂eq), approximately 15 percent of cropland net GHG (N₂O and soil carbon) can be mitigated. More than 190 million tCO₂eq (about 22 percent to 23 percent of baseline emissions, depending on which year is analyzed) are mitigated at less than \$45/tCO₂eq in 2010 and 2020, but costs begin to rise rapidly beyond that point. Mitigation levels do not substantially increase at higher prices, given the mitigation options considered here.

Negative costs result from options with cost savings because of lower applications of fertilizers while maintaining yields, whereas high-cost options are those where revenues decline as yields decline in response to suboptimal fertilizer applications. Negative cost options are consistent with previous studies, finding large potential agricultural mitigation from “no-regret” options. The fact that farmers are not adopting options that seemingly would increase profitability indicates that this analysis may not capture some costs barriers to adoption exist, such as increased variability of profits or complexity of management requirements.

Table 1-11: Croplands Mitigation Option Detail for Key Regions

	United States					EU-15					Brazil				
	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (% from baseline)			
Croplands															
Nitrogen inhibitor—wheat—f	6.6%	\$26	2.33	1.3%	9.6%	-\$13	2.568	2.8%	11.7%	\$27	0.029	0.1%			
Nitrogen inhibitor—wheat—irri	7.4%	\$11	0.17	0.1%	10.0%	-\$18	1.107	1.2%	11.9%	\$25	0.000	0.0%			
Nitrogen inhibitor—maize—f	3.6%	\$9	2.99	1.7%	2.7%	\$15	0.171	0.2%	25.5%	\$21	1.180	4.0%			
Nitrogen inhibitor—maize—irri	3.4%	\$2	0.58	0.3%	2.3%	\$13	0.061	0.1%	NA	NA	NA	NA			
Nitrogen inhibitor—soybean—f	0.6%	\$210	0.53	0.3%	0.4%	\$384	0.001	0.0%	2.4%	\$125	0.231	0.8%			
Nitrogen inhibitor—soybean—irri	0.5%	\$210	0.05	0.0%	0.3%	\$323	0.000	0.0%	NA	NA	NA	NA			
Split fertilization—wheat—f	8.6%	-\$64	2.00	1.1%	2.7%	\$48	0.542	0.6%	19.8%	-\$69	0.039	0.1%			
Split fertilization—wheat—irri	8.3%	-\$67	0.14	0.1%	3.0%	\$44	0.214	0.2%	19.3%	-\$70	0.000	0.0%			
Split fertilization—maize—f	9.4%	-\$38	7.59	4.2%	3.8%	\$13	0.154	0.2%	11.4%	-\$60	0.173	0.6%			
Split fertilization—maize—irri	8.9%	-\$38	1.60	0.9%	4.3%	\$5	0.077	0.1%	NA	NA	NA	NA			
Split fertilization—soybean—f	1.0%	\$188	0.33	0.2%	0.0%	\$190,338	0.000	0.0%	0.6%	\$76	0.081	0.3%			
Split fertilization—soybean—irri	0.8%	\$298	0.03	0.0%	0.0%	\$366,480	0.000	0.0%	NA	NA	NA	NA			
Reduce fertilizer to 70% of base—wheat—f	-16.6%	\$267	0.81	0.5%	-19.1%	\$114	0.798	0.9%	-12.2%	\$69	0.008	0.0%			
Reduce fertilizer to 70% of base—wheat—irri	-16.3%	\$296	0.06	0.0%	-19.0%	\$170	0.260	0.3%	-12.2%	\$76	0.000	0.0%			
Reduce fertilizer to 70% of base—maize—f	-23.6%	-\$613	-1.12	-0.6%	-15.9%	-\$22,944	-0.001	0.0%	-23.7%	\$109	-0.062	-0.2%			
Reduce fertilizer to 70% of base—maize—irri	-22.7%	-\$553	-0.28	-0.2%	-15.4%	-\$445	-0.018	0.0%	NA	NA	NA	NA			
Reduce fertilizer to 70% of base—soybean—f	-0.6%	-\$44	0.33	0.2%	0.0%	-\$64	0.000	0.0%	-0.5%	-\$14	0.088	0.3%			
Reduce fertilizer to 70% of base—soybean—irri	-0.5%	-\$43	0.03	0.0%	0.0%	-\$40	0.000	0.0%	NA	NA	NA	NA			
Reduce fertilizer to 80% of base—wheat—f	-11.0%	\$249	0.57	0.3%	-13.0%	\$117	0.553	0.6%	-8.1%	\$70	0.005	0.0%			
Reduce fertilizer to 80% of base—wheat—irri	-10.9%	\$293	0.04	0.0%	-12.9%	\$174	0.176	0.2%	-8.2%	\$76	0.000	0.0%			
Reduce fertilizer to 80% of base—maize—f	-15.8%	-\$766	-0.60	-0.3%	-10.4%	\$1,231	0.010	0.0%	-16.3%	\$71	-0.057	-0.2%			
Reduce fertilizer to 80% of base—maize—irri	-15.2%	-\$628	-0.17	-0.1%	-10.3%	-\$635	-0.009	0.0%	NA	NA	NA	NA			
Reduce fertilizer to 80% of base—soybean—f	-0.4%	-\$45	0.22	0.1%	0.0%	-\$57	0.000	0.0%	-0.4%	-\$14	0.059	0.2%			

(continued)

Table 1-11: Croplands Mitigation Option Detail for Key Regions (continued)

	United States				EU-15				Brazil			
	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)
Croplands												
Reduce fertilizer to 80% of base—soybean-irri	-0.3%	-\$45	0.02	0.0%	0.0%	-\$46	0.000	0.0%	NA	NA	NA	NA
Reduce fertilizer to 90% of base—wheat-rf	-5.6%	\$264	0.28	0.2%	-6.5%	\$116	0.284	0.3%	-4.1%	\$69	0.003	0.0%
Reduce fertilizer to 90% of base—wheat-irri	-5.4%	\$275	0.02	0.0%	-6.5%	\$174	0.090	0.1%	-4.1%	\$74	0.000	0.0%
Reduce fertilizer to 90% of base—maize-rf	-7.9%	-\$1,037	-0.22	-0.1%	-5.1%	\$606	0.009	0.0%	-8.4%	\$50	-0.035	-0.1%
Reduce fertilizer to 90% of base—maize-irri	-7.6%	-\$759	-0.07	0.0%	-5.1%	-\$941	-0.003	0.0%	NA	NA	NA	NA
Reduce fertilizer to 90% of base—soybean-rf	-0.2%	-\$47	0.11	0.1%	0.0%	-\$65	0.000	0.0%	-0.2%	-\$15	0.029	0.1%
Reduce fertilizer to 90% of base—soybean-irri	-0.1%	-\$46	0.01	0.0%	0.0%	-\$40	0.000	0.0%	NA	NA	NA	NA
Convert conventional tillage to no-till—wheat-rf	1.5%	-\$63	2.10	1.2%	1.2%	\$17	-7.160	-7.7%	0.6%	-\$24	0.015	0.0%
Convert conventional tillage to no-till—wheat-irri	0.9%	-\$80	0.11	0.1%	0.3%	\$12	-3.977	-4.3%	0.4%	-\$24	0.000	0.0%
Convert conventional tillage to no-till—maize-rf	1.6%	-\$87	4.14	2.3%	0.1%	\$135	-0.221	-0.2%	0.5%	-\$15	0.369	1.3%
Convert conventional tillage to no-till—maize-irri	0.9%	-\$89	0.61	0.3%	-2.5%	\$40	-0.137	-0.1%	NA	NA	NA	NA
Convert conventional tillage to no-till—soybean-rf	0.2%	-\$154	1.37	0.8%	0.5%	-\$317	0.005	0.0%	0.1%	-\$103	0.237	0.8%
Convert conventional tillage to no-till—soybean-irri	0.3%	-\$46	0.12	0.1%	0.6%	-\$135	0.001	0.0%	NA	NA	NA	NA

EU-15 = European Union; NA = Data unavailable.

(continued)

Table 1-11: Croplands Mitigation Option Detail for Key Regions (continued)

Cropland	China				India			
	Change in Output Yield (% from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (%) from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (%) from baseline)
Nitrogen inhibitor—wheat-rf	5.0%	\$58	0.282	0.3%	2.5%	\$208	0.070	0.1%
Nitrogen inhibitor—wheat-irri	5.6%	\$31	1.051	1.1%	3.9%	\$84	0.519	0.8%
Nitrogen inhibitor—maize-rf	2.2%	\$49	0.788	0.8%	26.0%	\$9	2.513	3.6%
Nitrogen inhibitor—maize-irri	2.3%	\$39	0.569	0.6%	24.2%	\$10	0.694	1.0%
Nitrogen inhibitor—soybean-rf	0.3%	\$175	0.074	0.1%	5.6%	\$85	0.129	0.2%
Nitrogen inhibitor—soybean-irri	0.2%	\$147	0.076	0.1%	5.4%	\$94	0.010	0.0%
Split fertilization—wheat-rf	3.6%	-\$1	0.102	0.1%	2.3%	\$21	0.027	0.0%
Split fertilization—wheat-irri	4.1%	-\$14	0.405	0.4%	3.6%	-\$5	0.335	0.5%
Split fertilization—maize-rf	1.7%	\$51	0.340	0.3%	12.7%	-\$24	0.848	1.2%
Split fertilization—maize-irri	1.8%	\$32	0.381	0.4%	12.7%	-\$34	0.219	0.3%
Split fertilization—soybean-rf	0.3%	\$534	0.018	0.0%	0.0%	\$0	—	0.0%
Split fertilization—soybean-irri	0.3%	\$449	0.025	0.0%	0.0%	\$0	—	0.0%
Reduce fertilizer to 70% of base—wheat-rf	-11.5%	\$30	0.321	0.3%	-8.6%	\$7	0.193	0.3%
Reduce fertilizer to 70% of base—wheat-irri	-13.4%	\$104	0.643	0.7%	-13.6%	\$208	0.282	0.4%
Reduce fertilizer to 70% of base—maize-rf	-16.0%	-\$226	-0.479	-0.5%	-7.9%	\$41	0.255	0.4%
Reduce fertilizer to 70% of base—maize-irri	-15.7%	-\$206	-0.424	-0.4%	-8.2%	\$53	0.082	0.1%
Reduce fertilizer to 70% of base—soybean-rf	-0.4%	-\$37	0.142	0.1%	0.0%	\$0	—	0.0%
Reduce fertilizer to 70% of base—soybean-irri	-0.3%	-\$39	0.118	0.1%	0.0%	\$0	—	0.0%
Reduce fertilizer to 80% of base—wheat-rf	-7.5%	\$29	0.217	0.2%	-5.6%	\$6	0.129	0.2%
Reduce fertilizer to 80% of base—wheat-irri	-8.9%	\$103	0.432	0.4%	-9.3%	\$229	0.175	0.3%
Reduce fertilizer to 80% of base—maize-rf	-10.5%	-\$249	-0.286	-0.3%	-5.3%	\$43	0.167	0.2%
Reduce fertilizer to 80% of base—maize-irri	-10.5%	-\$223	-0.262	-0.3%	-5.5%	\$55	0.054	0.1%
Reduce fertilizer to 80% of base—soybean-rf	-0.3%	-\$36	0.096	0.1%	0.0%	\$0	—	0.0%
Reduce fertilizer to 80% of base—soybean-irri	-0.2%	-\$38	0.080	0.1%	0.0%	\$0	—	0.0%
Reduce fertilizer to 90% of base—wheat-rf	-3.8%	\$28	0.110	0.1%	-2.8%	\$6	0.065	0.1%
Reduce fertilizer to 90% of base—wheat-irri	-4.4%	\$101	0.220	0.2%	-4.7%	\$247	0.083	0.1%
Reduce fertilizer to 90% of base—maize-rf	-5.2%	-\$276	-0.127	-0.1%	-2.7%	\$45	0.081	0.1%
Reduce fertilizer to 90% of base—maize-irri	-5.2%	-\$240	-0.121	-0.1%	-2.8%	\$59	0.026	0.0%
Reduce fertilizer to 90% of base—soybean-rf	-0.1%	-\$36	0.049	0.1%	0.0%	\$0	—	0.0%
Reduce fertilizer to 90% of base—soybean-irri	-0.1%	-\$38	0.040	0.0%	0.0%	\$0	—	0.0%
Convert conventional tillage to no-till—wheat-rf	1.4%	-\$65	0.283	0.3%	2.7%	-\$29	0.150	0.2%
Convert conventional tillage to no-till—wheat-irri	2.0%	-\$69	1.046	1.1%	5.5%	-\$61	0.954	1.4%
Convert conventional tillage to no-till—maize-rf	1.4%	-\$86	1.143	1.2%	2.7%	-\$23	1.294	1.9%
Convert conventional tillage to no-till—maize-irri	1.3%	-\$84	0.654	0.7%	2.0%	-\$23	0.329	0.5%
Convert conventional tillage to no-till—soybean-rf	0.0%	-\$168	0.152	0.2%	1.3%	-\$70	0.131	0.2%
Convert conventional tillage to no-till—soybean-irri	0.0%	-\$41	0.136	0.1%	1.3%	-\$23	0.010	0.0%

EU-15 = European Union; NA = Data unavailable.

Table 1-12: Croplands: Percentage Reductions from Baselines at Different \$/tCO₂eq Prices

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	11.1%	12.8%	13.9%	14.5%	14.5%	10.6%	13.5%	13.6%	14.0%	14.2%
Annex I	20.6%	23.2%	29.7%	30.2%	30.9%	19.6%	20.7%	24.2%	28.6%	29.2%
Australia/New Zealand	21.2%	21.2%	24.9%	34.7%	34.7%	21.9%	21.9%	26.1%	36.1%	36.1%
Brazil	5.3%	5.3%	13.3%	13.3%	13.3%	4.5%	4.5%	12.3%	12.4%	12.4%
China	6.4%	6.4%	6.7%	10.1%	12.7%	5.8%	6.3%	7.3%	10.5%	12.5%
Eastern Europe	14.6%	18.8%	21.0%	21.5%	24.1%	13.5%	17.9%	20.8%	20.8%	20.8%
EU-15	11.9%	12.7%	13.0%	13.7%	15.5%	10.8%	10.8%	11.4%	11.7%	13.8%
India	6.2%	11.4%	11.4%	12.0%	12.4%	5.8%	11.5%	11.5%	11.5%	11.5%
Japan	11.8%	11.8%	11.8%	11.8%	12.5%	11.0%	11.0%	11.0%	11.6%	11.6%
Mexico	10.8%	14.3%	23.4%	23.4%	23.4%	10.5%	23.2%	23.2%	23.2%	23.2%
Non-OECD Annex I	28.3%	28.3%	47.8%	47.9%	48.3%	28.0%	28.0%	31.7%	47.5%	47.9%
OECD	18.0%	21.4%	23.8%	24.5%	25.0%	17.0%	18.7%	22.0%	22.9%	23.5%
Russian Federation	28.3%	28.3%	47.8%	47.9%	48.3%	28.0%	28.0%	31.7%	47.5%	47.9%
South & SE Asia	8.1%	8.3%	9.6%	13.5%	14.4%	8.3%	8.4%	11.0%	14.0%	14.3%
United States	21.7%	25.9%	28.5%	28.5%	28.5%	20.3%	21.0%	26.5%	26.5%	26.5%
World Total	15.4%	17.6%	22.0%	23.1%	24.0%	14.6%	16.2%	18.8%	22.0%	22.7%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

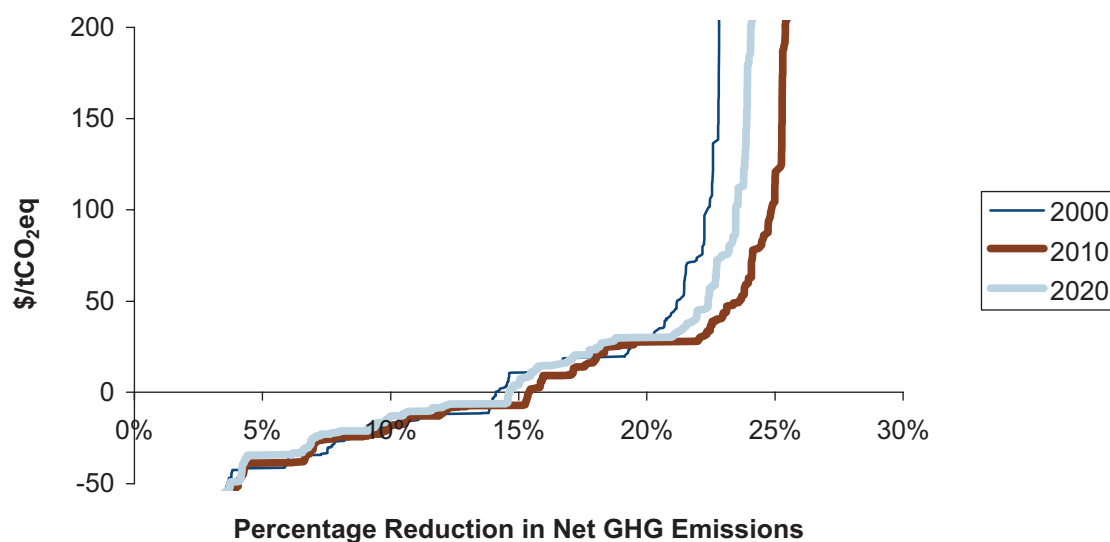
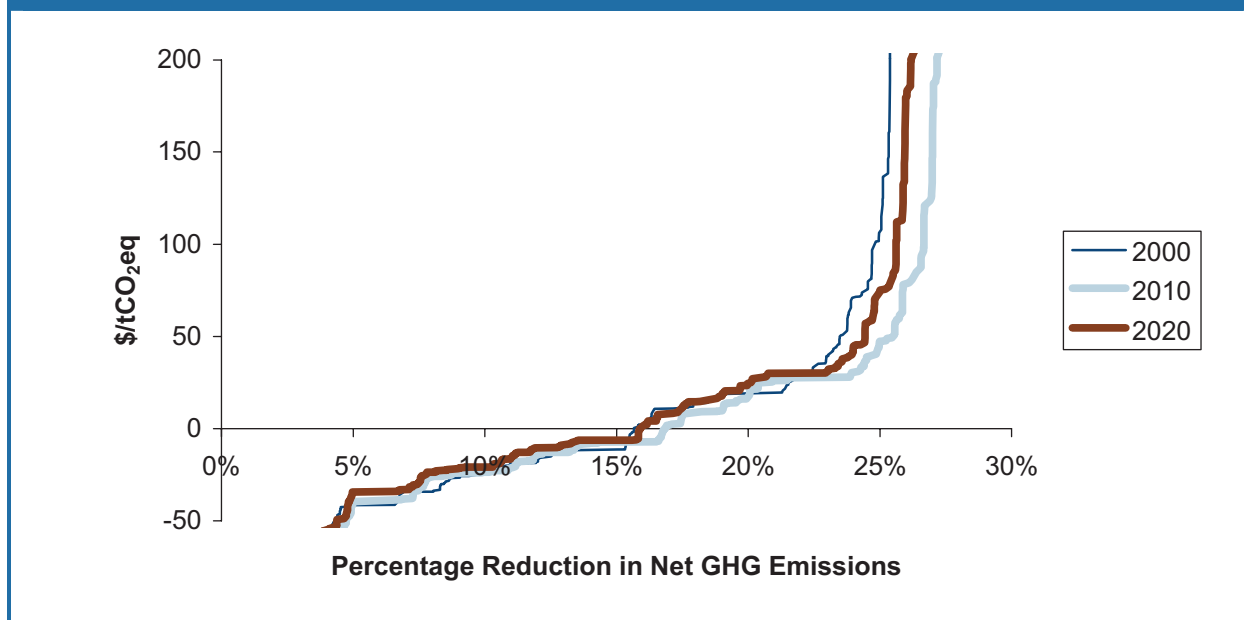
Figure 1-7: Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, 2000–2020

Figure 1-8 shows the sensitivity of the global cropland MAC when only the three options that were most effective at mitigating net GHGs (nitrogen inhibitors, split fertilization, and no till) are applied. The excluded options (reducing baseline levels of nitrogen fertilizer by varying amounts) had little impact on net emissions at the global scale. As expected, the MAC with only the three most effective options—where these options are each essentially applied to one-third of the cropland base—shows greater mitigation.

Figure 1-8: Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, Allocating Adoption of Mitigation Strategies to the Three Most Effective Options Only, 2000–2020



Figures 1-9, 1-10, 1-11, and 1-12 show the MACs for four major regions of the world—the United States, EU-15, FSU, and China. Each of those figures show simulated mitigation potential assuming equal adoption of the six mitigation options included for croplands. If mitigation strategies were limited to the three most effective options for emissions reductions, excluding the fertilizer reduction options that have little to no impact on net greenhouse gas in our DAYCENT model runs, total mitigation potential would increase. This is analogous to the change at the global level, observed in Figures 1-7 and 1-8. Percentage emissions reductions vary substantially, from less than 15 percent for China up to almost 50 percent in FSU. Among these four regions, the FSU has the largest emissions reduction potential, followed closely by the United States: both have emissions reductions above 50 MtCO₂eq at less than \$50/tCO₂eq. EU-15 and China have less than one-third of the emissions reductions of the FSU or United States, with potential reductions of 10 MtCO₂eq to 15 MtCO₂eq at \$50/tCO₂eq.

Figure 1-9: MAC for Net Greenhouse Gas Emissions from Cropland Management in the United States, Holding Area Constant, 2000–2020

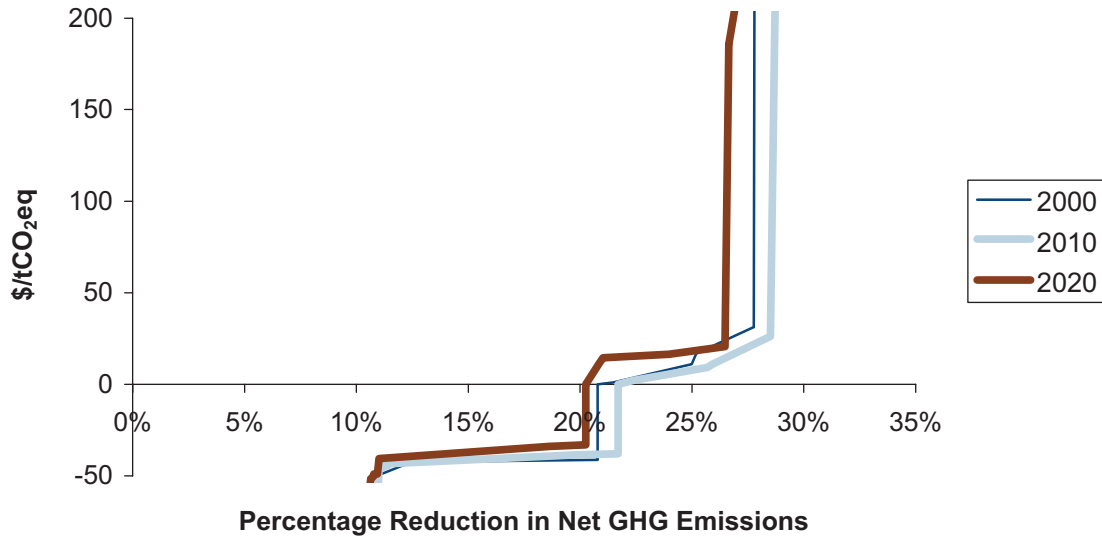


Figure 1-10: MAC for Net Greenhouse Gas Emissions from Cropland Management in the EU-15, Holding Area Constant, 2000–2020

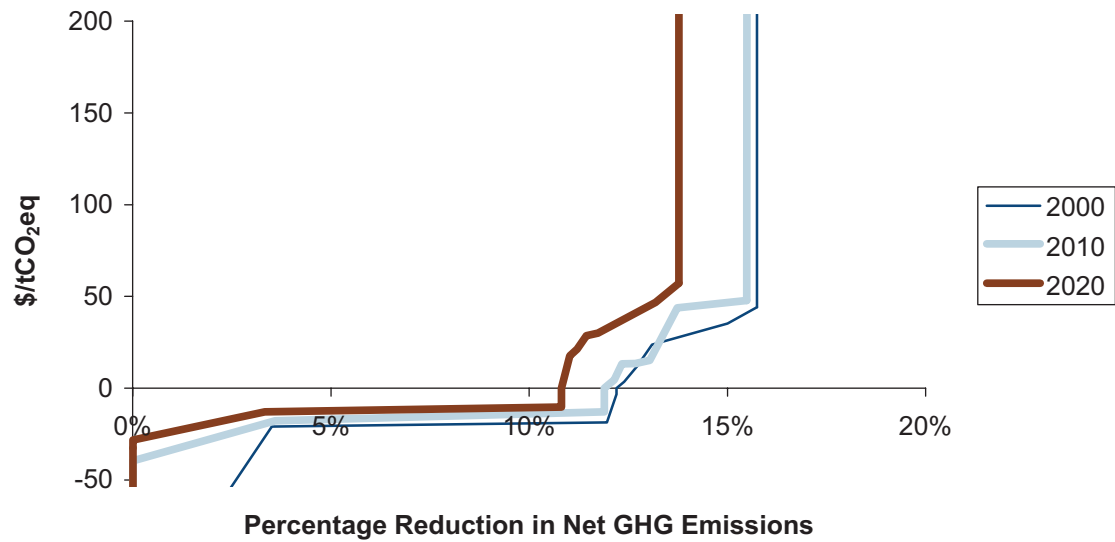


Figure 1-11: MAC for Net Greenhouse Gas Emissions from Cropland Management in the FSU, Holding Area Constant, 2000–2020

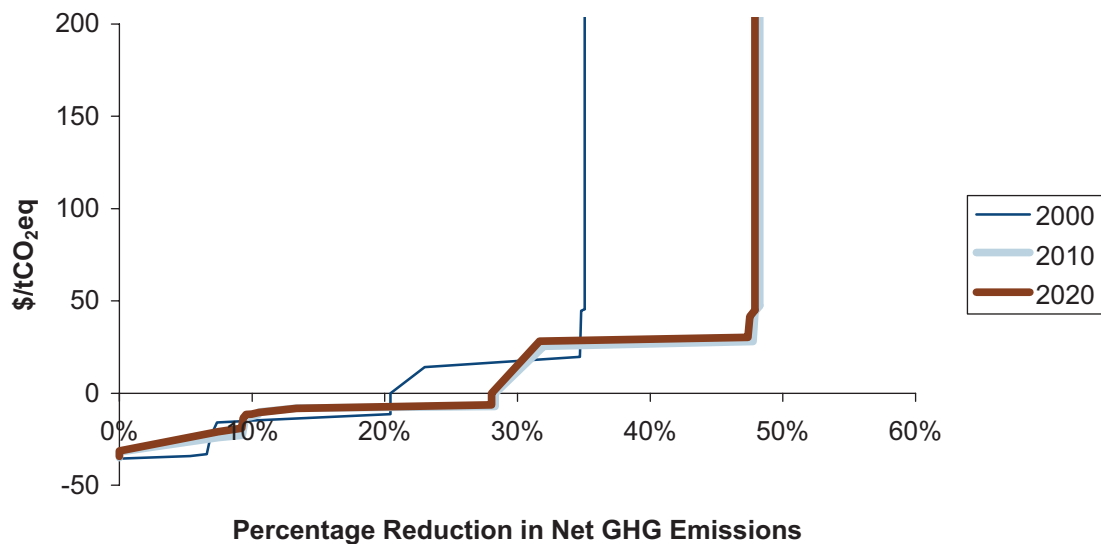
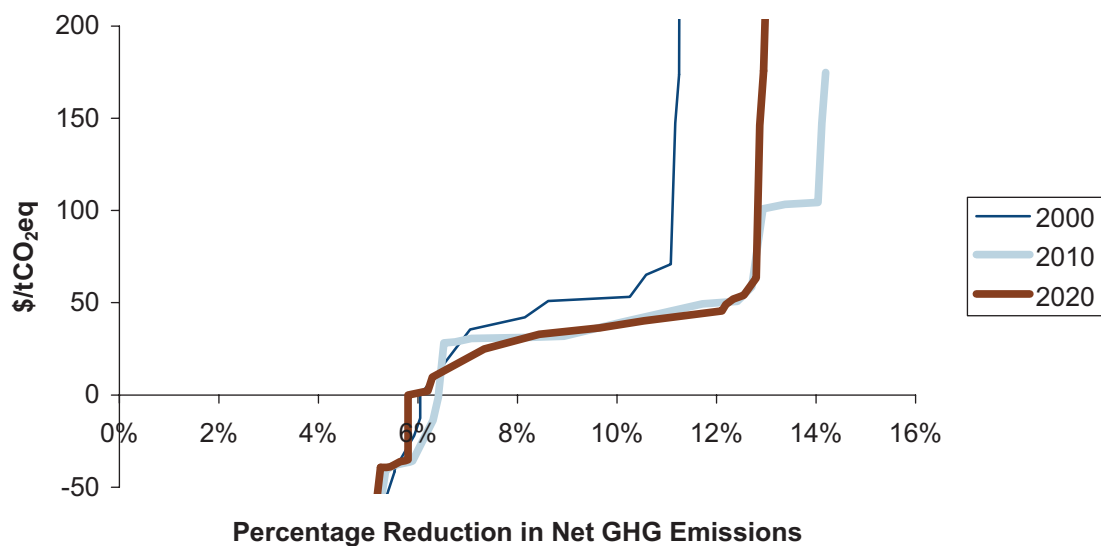


Figure 1-12: MAC for Net Greenhouse Gas Emissions from Cropland Management in China, Holding Area Constant, 2000–2020



V.3.3 Baselines, Mitigation Costs, and MACs for Rice Cultivation

Table 1-13 presents estimates of baseline net GHG emissions from rice cultivation by region by year used in this analysis. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-13: Baseline Emissions from Rice Cultivation from DNDC Estimates (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	—	—	—
Annex I	45	28	27
Australia/New Zealand	—	—	—
Brazil	—	—	—
China	385	301	302
Eastern Europe	—	—	—
EU-15	—	—	—
India	127	111	122
Japan	45	28	27
Mexico	—	—	—
Non-OECD Annex I	—	—	—
OECD	63	43	43
Russian Federation	—	—	—
South & SE Asia	929	583	594
United States	—	—	—
World Total	1,504	1,038	1,062

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-14 presents information on the yield effects, emissions reductions, and costs associated with individual rice cultivation mitigation options for China and India.

Table 1-15 provides estimates of the percentage reduction in net GHG emissions (relative to the rice cultivation baseline used in this analysis) that could potentially be achieved at prices between \$0/tCO₂eq and \$60/tCO₂eq for both 2010 and 2020 in major regions around the world.

Figure 1-13 shows the MACs estimated for 2000, 2010, and 2020. This outward shift in the curve reflects changes in baseline emissions, commodity prices, labor rates, and other factors over time. Total global mitigation for rice CH₄ is estimated to be around 3 percent at negative or zero cost and about 13 percent at \$45/tCO₂eq in 2000. After that level, costs rise very rapidly. By 2010, global mitigation is estimated to have increased to about 11 percent at negative or zero cost and 24 percent at \$45/tCO₂eq. Between 2010 and 2020, there is little change in the MAC throughout most of its range.

Figures 1-14 and 1-15 display the MACs for the key rice-producing regions of India and China, respectively. In both regions, the percentage emissions reduction is higher in 2010 than in 2000, but the curve shifts inward in 2020. This is largely due to substantial changes in the baseline emissions over time that are changing the reductions in net GHG relative to baseline conditions available. For instance, baseline emissions from China are projected to decline substantially over time, leaving fewer emissions to be abated in future years. DNDC simulations project baseline emissions from rice cultivation in China to fall by 21.5 percent between 2000 and 2020, from 384.9 MtCO₂eq in 2000 to 302.1 MtCO₂eq by 2020.

Table 1-14: Rice Cultivation Mitigation Option Detail for Key Regions

Option Labels	China				India			
	Breakeven Cost (\$tCO ₂ eq)	Emission Reduction (absolute, MtCO ₂ eq)	Emission Reduction (1% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost (\$tCO ₂ eq)	Emission Reduction (absolute, MtCO ₂ eq)	Emission Reduction (1% from baseline)	Change in Output Yield (% from baseline)
Midseason drainage—rice(rf)	NA	NA	NA	NA	NA	NA	NA	NA
Midseason drainage—rice(irri)	3.2%	−\$11.4	3.5	1.2%	0.7%	4	8.9	8.0%
Shallow flooding—rice(rf)	NA	NA	NA	NA	NA	NA	NA	NA
Shallow flooding—rice(irri)	5.5%	−\$1.9	28.6	9.5%	0.3%	7	14.9	13.4%
Offseason straw—rice(rf)	NA	NA	NA	NA	0.0%	81	0.3	0.3%
Offseason straw—rice(irri)	2.1%	−\$3.6	2.2	0.7%	0.0%	9	5.7	5.2%
Sulfate fertilizer—rice(rf)	NA	NA	NA	NA	0.0%	89	0.3	0.3%
Sulfate fertilizer—rice(irri)	1.8%	−\$2.9	13.1	4.4%	−0.3%	19	2.0	1.8%
Slow-release fertilizers—rice(rf)	NA	NA	NA	NA	0.0%	248	0.3	0.2%
Slow-release fertilizer—rice(irri)	5.4%	\$27.9	−2.3	−0.8%	−0.3%	−319	−0.3	−0.2%
Switch to upland rice—rice(rf)	NA	NA	NA	NA	6.1%	21	−3.9	−3.5%
Switch to upland rice—rice(irri)	−15.0%	\$10.1	45.1	15.0%	−32.9%	62	15.7	14.1%

NA = Data unavailable.

Table 1-15: Rice Cultivation: Percentage Reductions from Baseline at Different \$/tCO₂eq Prices

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Annex I	1.6%	24.1%	24.1%	24.1%	24.1%	1.6%	24.4%	24.4%	24.4%	24.4%
Australia/New Zealand	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Brazil	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
China	15.8%	30.8%	30.0%	30.0%	30.0%	13.1%	26.3%	27.0%	27.0%	27.0%
Eastern Europe	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
EU-15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
India	-0.2%	26.4%	24.7%	24.7%	24.7%	-0.3%	25.9%	25.9%	25.9%	25.9%
Japan	1.6%	24.1%	24.1%	24.1%	24.1%	1.6%	24.4%	24.4%	24.4%	24.4%
Mexico	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Non-OECD Annex I	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
OECD	4.0%	19.5%	24.8%	24.8%	24.8%	4.4%	25.0%	25.0%	25.0%	25.0%
Russian Federation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
South & SE Asia	10.4%	16.6%	16.8%	20.7%	22.3%	12.1%	19.1%	19.1%	22.7%	22.7%
United States	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
World Total	10.5%	21.9%	21.8%	24.0%	24.9%	10.7%	22.1%	22.4%	24.4%	24.4%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; NA = Data unavailable.

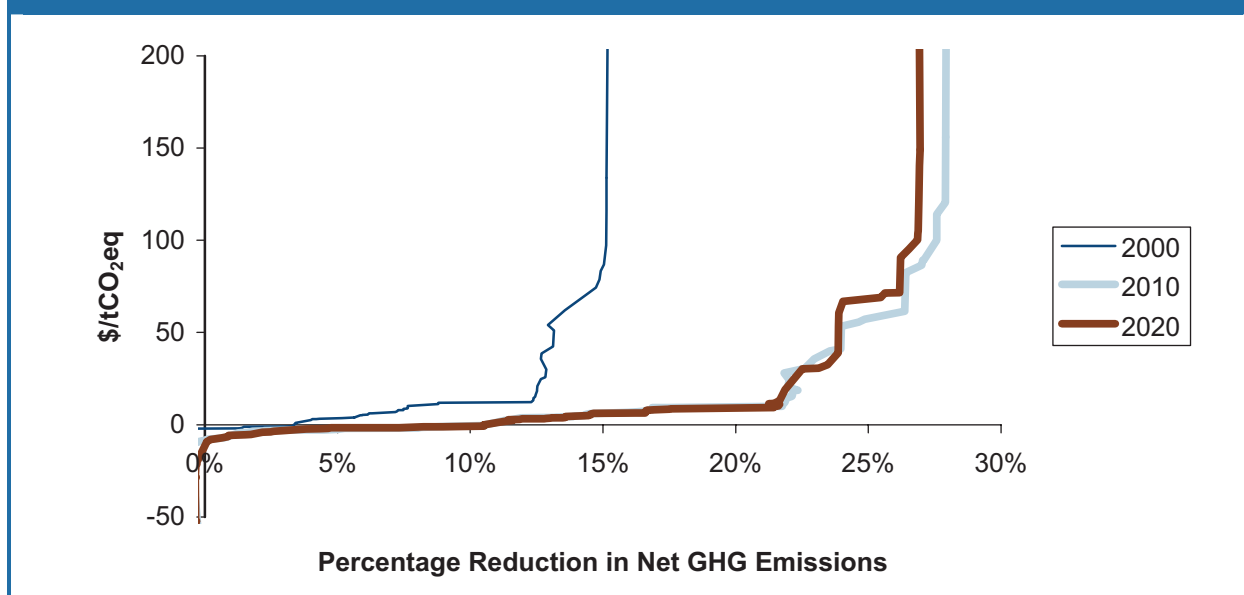
Figure 1-13: Global MAC for Net Greenhouse Gas Emissions from Rice Cultivation, Holding Area Constant, 2000–2020

Figure 1-14: MAC for Net Greenhouse Gas Emissions from Rice Cultivation in India, Holding Area Constant, 2000–2020

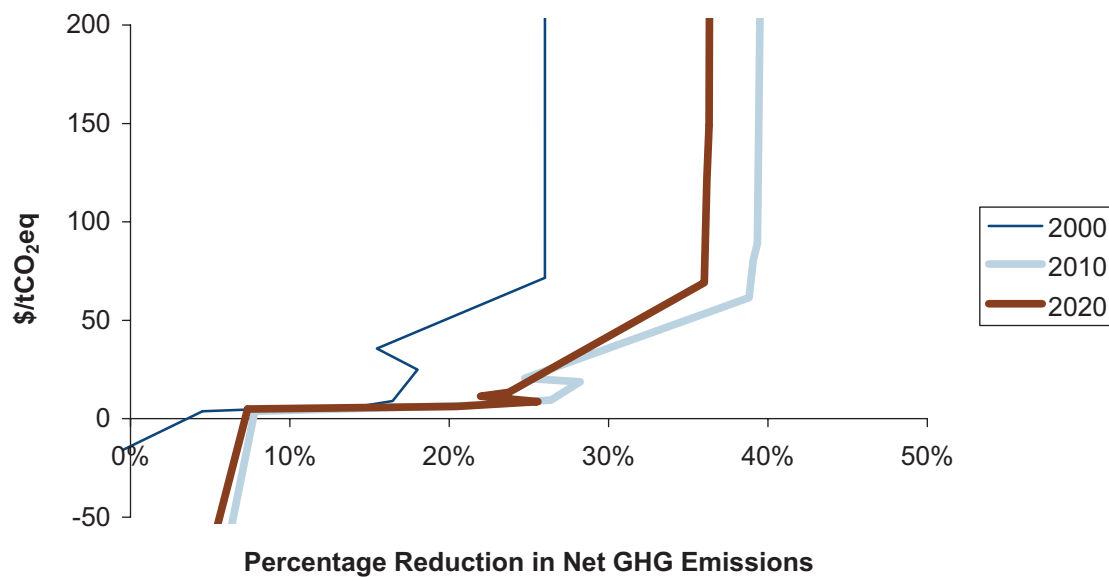
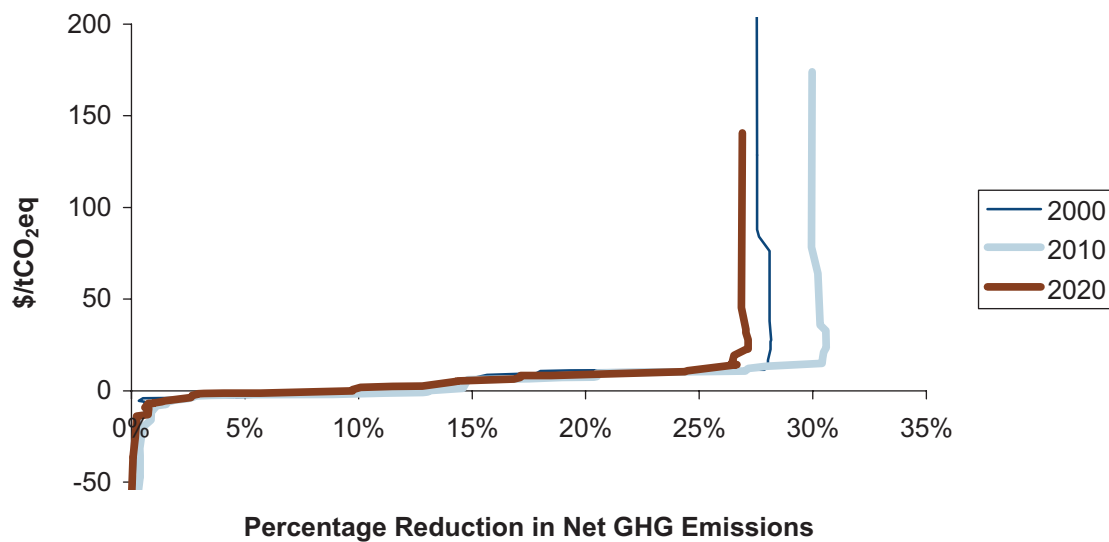


Figure 1-15: MAC for Net Greenhouse Gas Emissions from Rice Cultivation in China, Holding Area Constant, 2000–2020



V.3.4 Baselines, Mitigation Costs, and MACs for Livestock Management

Table 1-16 presents estimates of baseline net GHG emissions from livestock enteric fermentation and manure management by region and by year. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-17 presents information on the yield effects, emissions reductions, and costs associated with individual livestock management mitigation options for the USA, EU-15, Brazil, China, and India.

Table 1-16: Baseline Emissions from Livestock Management from USEPA (2006) (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	271	332	395
Annex I	704	718	748
Australia/New Zealand	91	93	94
Brazil	222	263	297
China	313	392	470
Eastern Europe	48	54	58
EU-15	222	203	202
India	224	260	286
Japan	20	21	22
Mexico	43	50	57
Non-OECD Annex I	111	131	150
OECD	642	644	663
Russian Federation	66	78	91
South & SE Asia	187	232	276
United States	171	173	171
World Total	2,220	2,548	2,867

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-17: Livestock Mitigation Option Detail for Key Regions

	United States				EU-15				Brazil			
	Change in Output Yield (%) from baseline	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)
Livestock												
Improved feed conversion—beef	0.2%	-\$1,126	-0.2	-0.1%	7.7%	\$238	-0.1	-0.1%	2.5%	\$102	1.3	0.5%
Improved feed conversion—dairy	0.0%	-\$655	-0.7	-0.4%	0.0%	\$5,335	0.1	0.0%	87.9%	\$187	-2.6	-1.0%
Antibiotics—beef	5.0%	-\$265	0.5	0.3%	5.0%	-\$121	0.7	0.4%	5.0%	-\$31	0.9	0.3%
bST—dairy	11.2%	\$888	-0.1	-0.1%	12.5%	-\$5,597	0.0	0.0%	12.5%	-\$1,097	-0.6	-0.2%
Propionate precursors—beef	5.0%	\$89	1.6	1.0%	5.0%	\$81	1.2	0.6%	5.0%	\$50	4.0	1.5%
Propionate precursors—dairy	5.0%	-\$68	1.4	0.8%	5.0%	\$183	2.1	1.0%	5.0%	\$322	1.6	0.6%
Antimethanogen—beef	5.0%	-\$60	1.6	1.0%	5.0%	-\$53	1.2	0.6%	5.0%	\$0	4.0	1.5%
Antimethanogen—sheep & goats	5.0%	\$184	0.1	0.1%	5.0%	\$327	1.5	0.8%	5.0%	\$131	0.4	0.2%
Antimethanogen—dairy	5.0%	-\$430	0.5	0.3%	5.0%	-\$288	0.8	0.4%	5.0%	\$20	0.7	0.3%
Intensive grazing—beef	0.0%	-\$70	2.2	1.3%	0.0%	\$24	1.7	0.8%	0.0%	-\$14	5.4	2.1%
Intensive grazing—dairy	-11.2%	\$371	0.8	0.5%	-11.2%	\$725	1.3	0.6%	-11.2%	\$78	1.0	0.4%
Complete-mix digester with engine—hogs	0.0%	\$25	2.5	1.4%	0.0%	\$7	3.9	1.9%	NA	NA	NA	NA
Complete-mix digester with engine—dairy	0.0%	\$12	1.7	1.0%	0.0%	-\$21	1.4	0.7%	NA	NA	NA	NA
Plug-flow digester with engine—dairy	0.0%	\$8	1.7	1.0%	0.0%	-\$40	1.4	0.7%	NA	NA	NA	NA
Fixed-film digester with engine—hogs	0.0%	\$31	2.5	1.4%	0.0%	\$15	3.9	1.9%	NA	NA	NA	NA
Fixed-film digester with engine—dairy	0.0%	\$16	1.7	1.0%	0.0%	-\$2	1.4	0.7%	NA	NA	NA	NA
Complete-mix digester without engine—hogs	0.0%	\$39	2.5	1.4%	0.0%	\$46	3.9	1.9%	NA	NA	NA	NA
Complete-mix digester without engine—dairy	0.0%	\$23	1.7	1.0%	0.0%	\$115	1.4	0.7%	NA	NA	NA	NA
Plug-flow digester without engine—dairy	0.0%	\$20	1.7	1.0%	0.0%	\$103	1.4	0.7%	NA	NA	NA	NA
Fixed-film digester without engine—hogs	0.0%	\$43	2.5	1.4%	0.0%	\$51	3.9	1.9%	NA	NA	NA	NA
Fixed-film digester without engine—dairy	0.0%	\$25	1.7	1.0%	0.0%	\$127	1.4	0.7%	NA	NA	NA	NA
Covered lagoon with engine—hogs	0.0%	-\$7	2.5	1.4%	0.0%	-\$30	3.9	1.9%	0.0%	-\$101	0.2	0.1%
Covered lagoon with engine—dairy	0.0%	\$5	1.7	1.0%	0.0%	-\$59	1.4	0.7%	0.0%	-\$447	0.2	0.1%

(continued)

Table 1-17: Livestock Mitigation Option Detail for Key Regions (continued)

	United States				EU-15				Brazil			
	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)	Change in Output Yield (%) from baseline)	Breakeven Cost (\$/tCO ₂ -eq)	Emissions Reduction (Absolute, MtCO ₂ -eq)	Emissions Reduction (% from baseline)
Livestock												
Covered lagoon without engine—hogs	0.0%	\$18	2.5	1.4%	0.0%	\$22	3.9	1.9%	0.0%	\$23	0.2	0.1%
Covered lagoon without engine—dairy	0.0%	\$18	1.7	1.0%	0.0%	\$90	1.4	0.7%	0.0%	\$402	0.2	0.1%
Domes cook fuel, light—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$135	0.1	0.0%
Domes cook fuel, light—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$2,145	0.1	0.1%
Polyethylene bags cook fuel, light—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$92	0.1	0.0%
Polyethylene bags cook fuel, light—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$553	0.1	0.1%
Covered lagoon cook fuel, light, shaft power—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$77	0.1	0.0%
Covered lagoon cook fuel, light, shaft power—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$345	0.1	0.1%
Flexible bag (pilot)—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$70	0.1	0.0%
Flexible bag (pilot)—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	-\$251	0.1	0.1%
EU-15 = European Union; NA = Data unavailable.												
(continued)												

EU-15 = European Union; NA = Data unavailable.

(continued)

Table 1-17: Livestock Mitigation Option Detail for Key Regions (continued)

Livestock	China				India			
	Change in Output Yield (% from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost (\$/tCO ₂ eq)	Emissions Reduction (Absolute, MtCO ₂ eq)	Emissions Reduction (% from baseline)
Improved feed conversion—beef	46.6%	-\$143	2.9	0.7%	69.0%	-\$382	0.7	0.3%
Improved feed conversion—dairy	6.2%	\$567	0.6	0.1%	16.9%	\$62	1.3	0.5%
Antibiotics—beef	5.0%	-\$41	0.6	0.1%	5.0%	-\$8	0.2	0.1%
bST—dairy	12.5%	-\$5,807	-0.2	-0.1%	12.5%	-\$6,438	-0.4	-0.2%
Propionate precursors—beef	5.0%	\$82	4.0	1.0%	5.0%	\$126	2.2	0.8%
Propionate precursors—dairy	5.0%	\$1,668	0.6	0.2%	5.0%	\$1,258	2.0	0.8%
Antimethanogen—beef	5.0%	\$5	4.0	1.0%	5.0%	\$15	2.2	0.8%
Antimethanogen—sheep & goats	5.0%	\$229	5.0	1.3%	5.0%	\$322	1.7	0.7%
Antimethanogen—dairy	5.0%	\$205	0.2	0.1%	5.0%	\$29	0.8	0.3%
Intensive grazing—beef	NA	NA	NA	NA	NA	NA	NA	NA
Intensive grazing—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Complete-mix digester with engine—hogs	0.0%	\$13	1.3	0.3%	NA	NA	NA	NA
Complete-mix digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Plug-flow digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Fixed-film digester with engine—hogs	0.0%	\$27	1.3	0.3%	NA	NA	NA	NA
Fixed-film digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Complete-mix digester without engine—hogs	0.0%	\$94	1.3	0.3%	NA	NA	NA	NA
Complete-mix digester without engine—dairy	0.0%	\$956	0.1	0.0%	NA	NA	NA	NA
Plug-flow digester without engine—dairy	0.0%	\$851	0.1	0.0%	NA	NA	NA	NA
Fixed-film digester without engine—hogs	0.0%	\$103	1.3	0.3%	NA	NA	NA	NA
Fixed-film digester without engine—dairy	0.0%	\$1,062	0.1	0.0%	NA	NA	NA	NA
Covered lagoon with engine—hogs	0.0%	-\$55	1.3	0.3%	NA	NA	NA	NA
Covered lagoon with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Covered lagoon without engine—hogs	0.0%	\$50	1.3	0.3%	0.0%	\$11	0.3	0.1%
Covered lagoon without engine—dairy	0.0%	\$745	0.1	0.0%	0.0%	\$448	0.7	0.3%
Domes cook fuel, light—hogs	0.0%	-\$101	0.8	0.2%	0.0%	-\$105	0.2	0.1%
Domes cook fuel, light—dairy	0.0%	-\$1,968	0.1	0.0%	0.0%	-\$4,508	0.4	0.2%
Polyethylene bags cook fuel, light—hogs	0.0%	-\$68	0.8	0.2%	0.0%	-\$74	0.2	0.1%
Polyethylene bags cook fuel, light—dairy	0.0%	-\$469	0.1	0.0%	0.0%	-\$1,165	0.4	0.2%
Covered lagoon cook fuel, light, shaft power—hogs	0.0%	-\$36	0.8	0.2%	0.0%	-\$65	0.2	0.1%
Covered lagoon cook fuel, light, shaft power—dairy	0.0%	-\$85	0.1	0.0%	0.0%	-\$936	0.4	0.2%
Flexible bag (pilot)—hogs	0.0%	-\$21	0.8	0.2%	0.0%	-\$61	0.2	0.1%
Flexible bag (pilot)—dairy	0.0%	\$89	0.1	0.0%	0.0%	-\$832	0.4	0.2%

EU-15 = European Union; NA = Data unavailable.

Table 1-18 provides estimates of the percentage reduction in net GHG emissions (relative to the livestock emissions baseline used in this analysis) that could potentially be achieved at prices between \$0/tCO₂eq and \$60/tCO₂eq for both 2010 and 2020 in major regions around the world.

Table 1-18: Livestock Management: Percentage Reductions from Baselines at Different \$/tCO₂eq Prices

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	0.7%	2.1%	2.6%	3.5%	3.6%	0.5%	2.1%	2.6%	3.5%	3.6%
Annex I	5.0%	6.9%	10.1%	11.3%	12.5%	4.9%	7.4%	10.3%	11.9%	12.7%
Australia/New Zealand	4.1%	4.3%	6.8%	7.5%	8.4%	4.2%	4.6%	7.2%	7.7%	8.7%
Brazil	2.9%	4.5%	4.9%	4.9%	6.5%	2.9%	4.5%	4.9%	4.9%	6.5%
China	2.0%	3.4%	3.7%	3.7%	4.1%	2.0%	3.4%	3.7%	3.7%	4.0%
Eastern Europe	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	3.5%
EU-15	6.3%	10.1%	13.0%	13.0%	16.9%	6.4%	10.3%	12.2%	15.2%	17.1%
India	1.2%	2.1%	2.5%	2.5%	2.5%	1.2%	2.5%	2.5%	2.5%	2.5%
Japan	4.0%	4.0%	4.4%	4.4%	4.4%	4.1%	4.1%	4.1%	4.4%	4.4%
Mexico	3.3%	3.3%	3.3%	3.4%	3.4%	3.3%	3.3%	3.3%	3.4%	3.4%
Non-OECD Annex I	2.5%	2.5%	2.5%	2.5%	2.5%	2.4%	2.4%	2.4%	2.4%	3.0%
OECD	5.4%	7.4%	11.1%	12.5%	13.8%	5.3%	8.1%	11.4%	13.3%	14.0%
Russian Federation	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.9%
South & SE Asia	3.9%	5.3%	6.1%	6.2%	6.6%	3.5%	4.6%	6.0%	6.0%	6.5%
United States	6.4%	9.4%	17.2%	21.4%	21.4%	6.3%	11.8%	19.8%	23.0%	23.0%
World Total	3.0%	4.4%	5.6%	6.1%	6.8%	2.9%	4.4%	5.5%	6.1%	6.7%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Total global mitigation for livestock management in 2020, holding the number of animals constant, is estimated to be 3 percent at negative or zero cost, reaching about 7 percent at \$60/tCO₂eq (Figure 1-16). Figure 1-17 shows the global MAC, holding production constant. The percentage of baseline emissions mitigated at \$60/tCO₂eq increases from just under 7 percent with a constant number of animals to over 10 percent with constant production. If other greenhouse gas benefits were included (e.g., soil carbon increases, cropland N₂O reductions for less feed), the estimates of greenhouse gas mitigation would be higher, but no model was identified to allow estimation of multigas impacts for livestock analogous to the DNDC and DAYCENT models used for cropland management and rice cultivation.

Figures 1-18, 1-19, 1-20, and 1-21 show the MACs for mitigation of greenhouse gas emissions from livestock management for the United States, China, India, and Brazil, respectively, holding the number of animals constant. Among these four regions, the United States has the greatest potential for relatively low-cost reductions in emissions in this sector, followed by China, Brazil, and India.

Because some options for mitigating emissions from enteric fermentation rely on improvements in yield resulting in fewer animals to achieve emissions reductions, assumptions about changes in livestock populations and production are important to examine for this sector. Thus, MACs are presented for the United States, China, India, and Brazil, assuming that production remains constant (Figures 1-22, 1-23, 1-24, and 1-25) to show the impact of this assumption. The differences between the two sets of graphs

Figure 1-16: Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Number of Animals Constant, 2000–2020

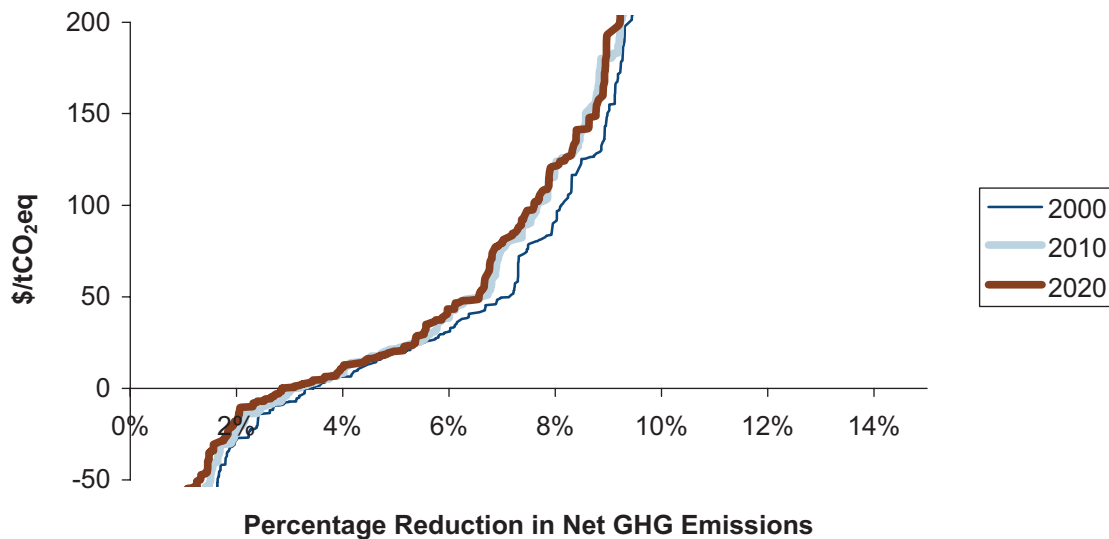


Figure 1-17: Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Production Constant, 2000–2020

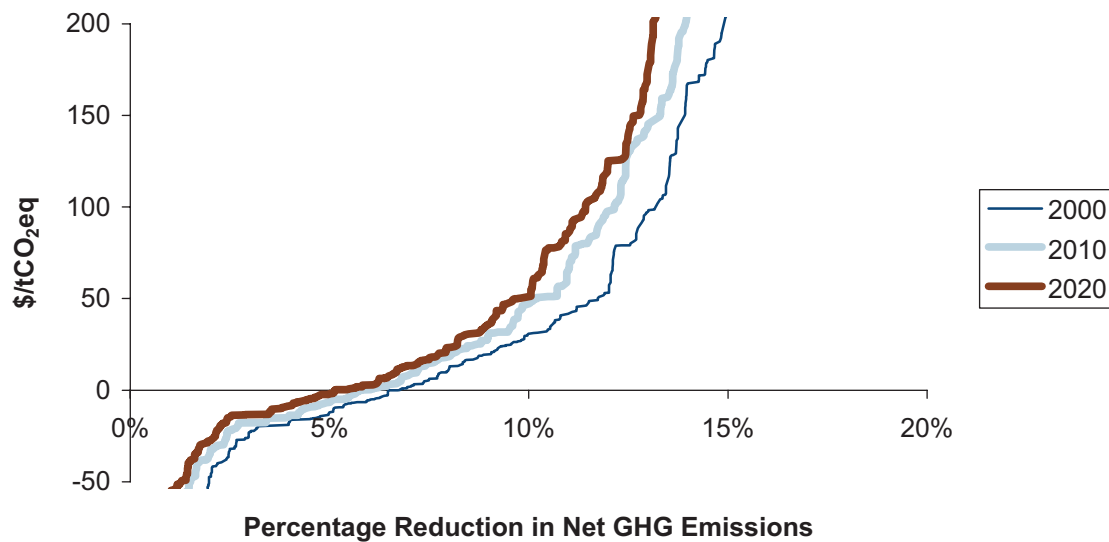


Figure 1-18: MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Number of Animals Constant, 2000–2020

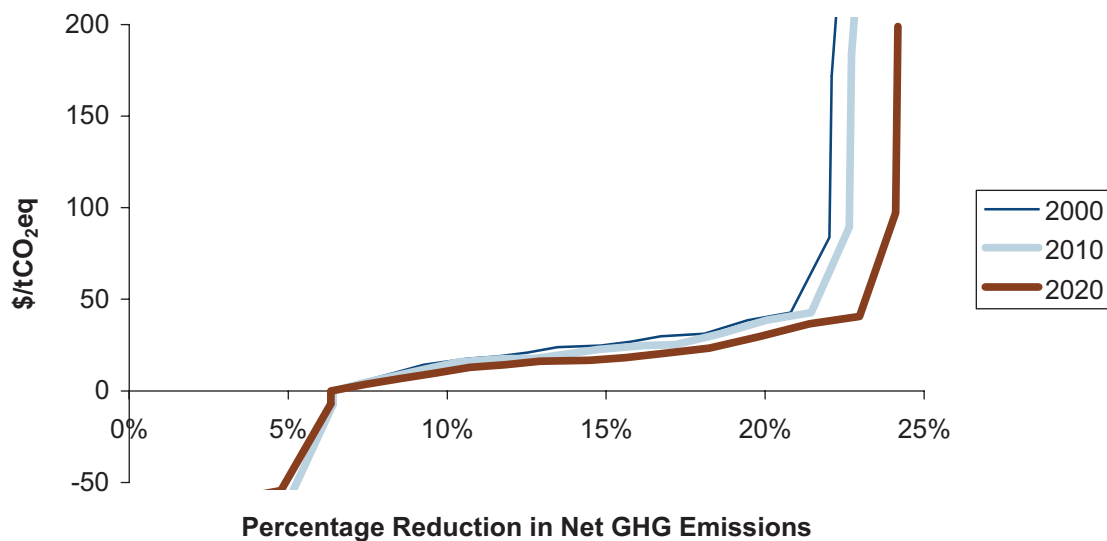


Figure 1-19: MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Number of Animals Constant, 2000–2020

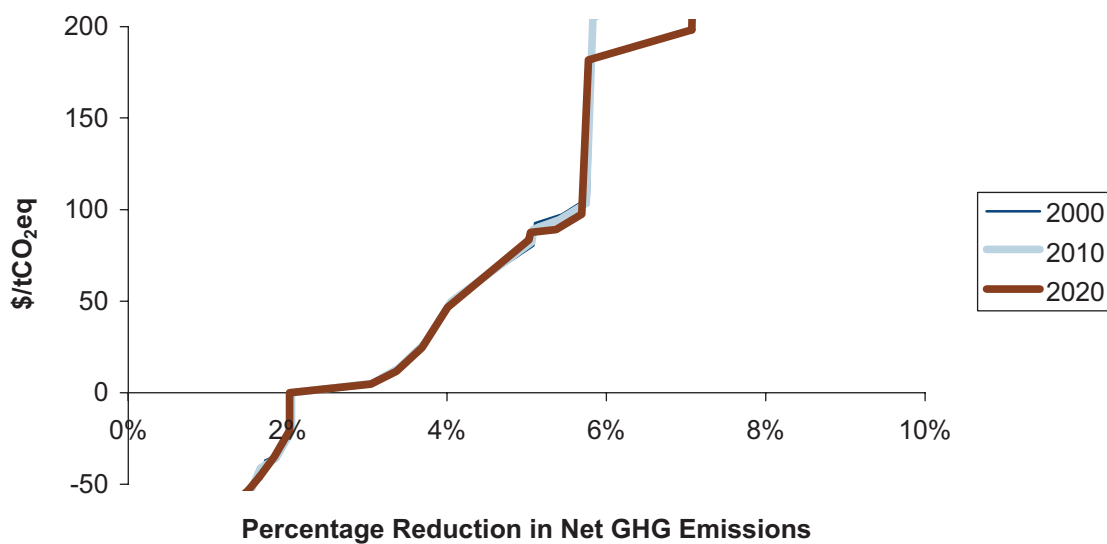


Figure 1-20: MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Number of Animals Constant, 2000–2020

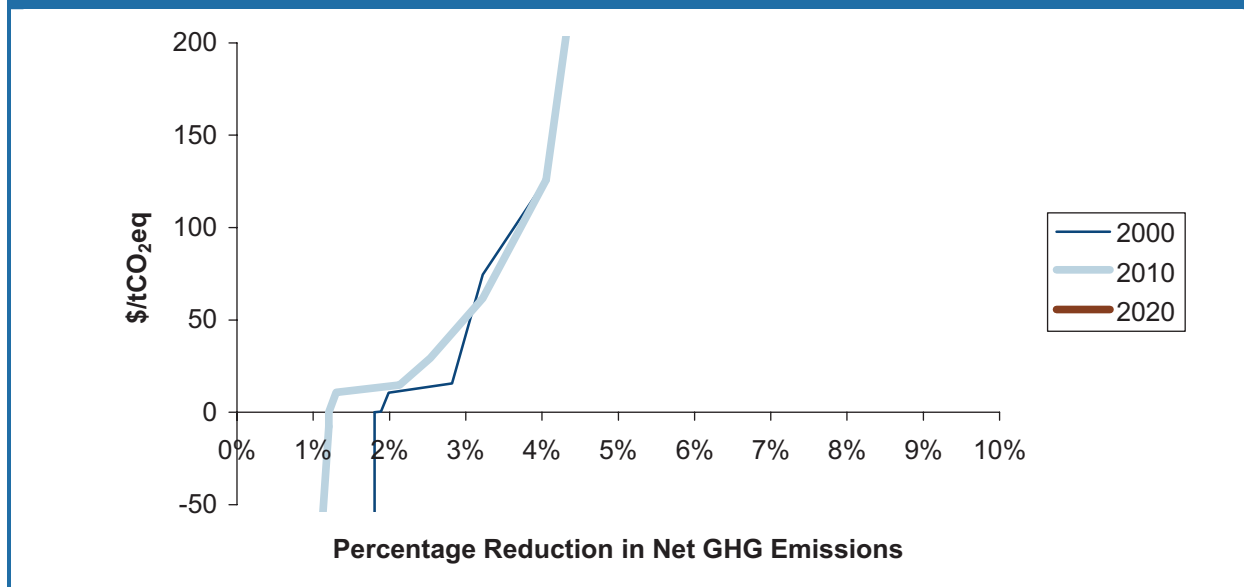


Figure 1-21: MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Number of Animals Constant, 2000–2020

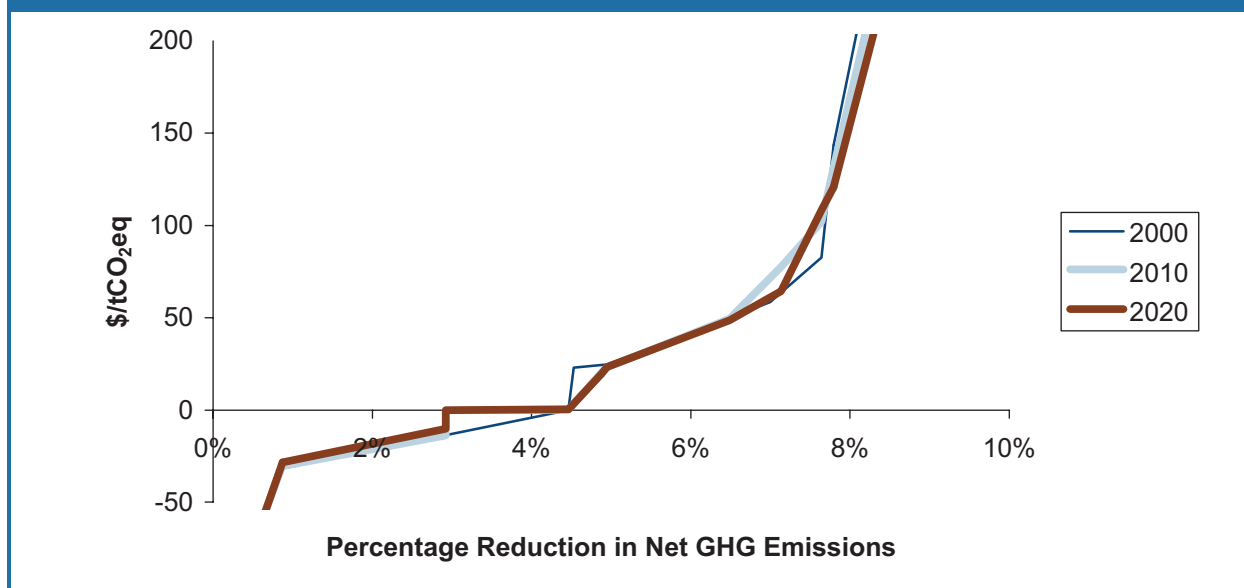


Figure 1-22: MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Production Constant, 2000–2020

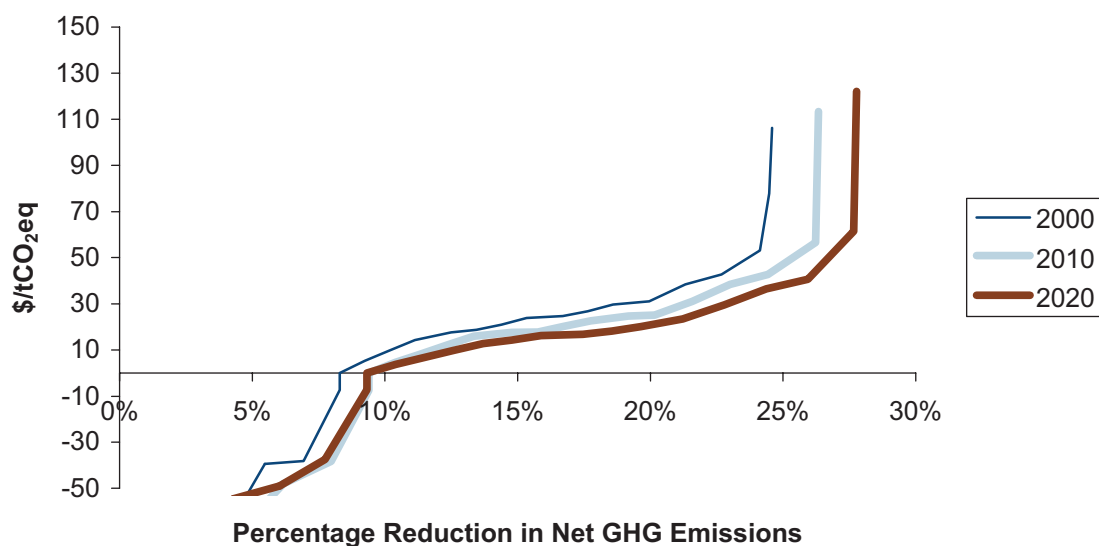


Figure 1-23: MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Production Constant, 2000–2020

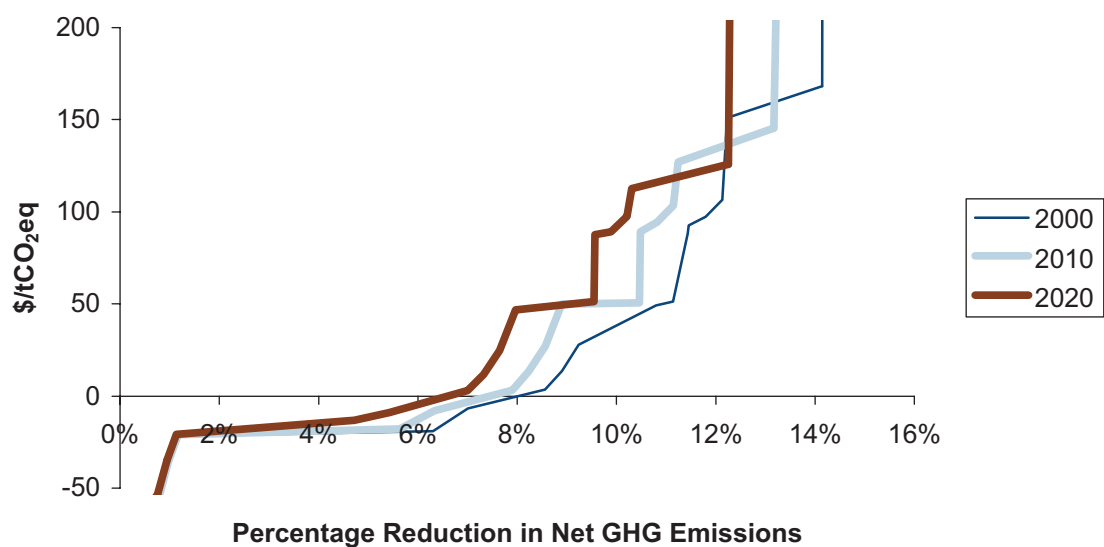


Figure 1-24: MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Production Constant, 2000–2020

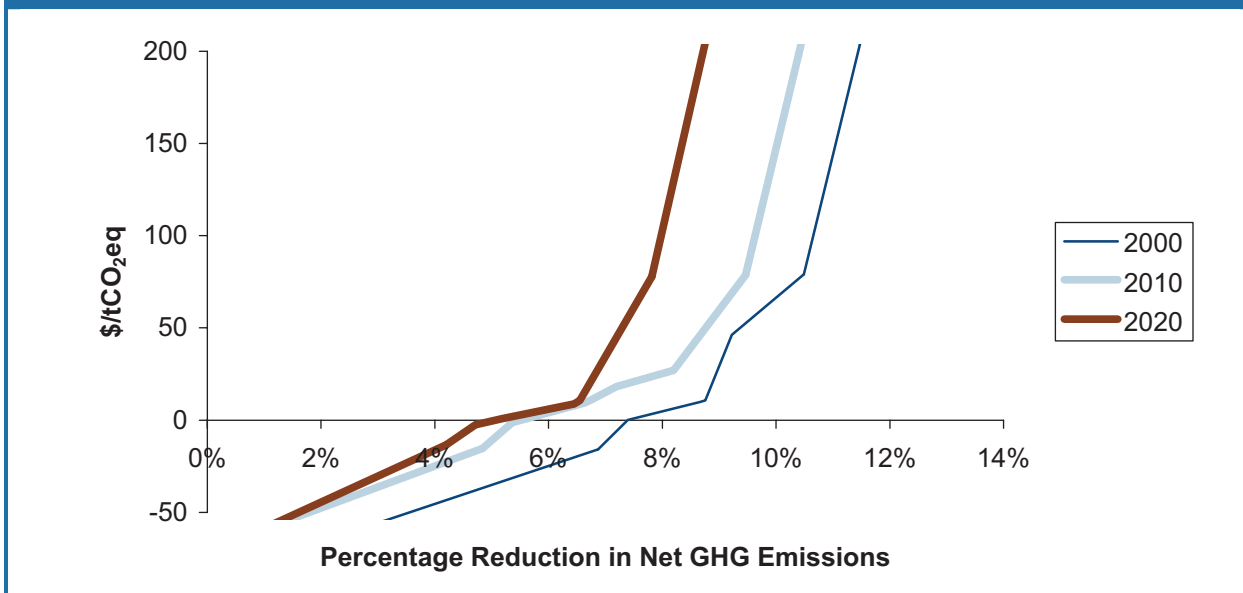
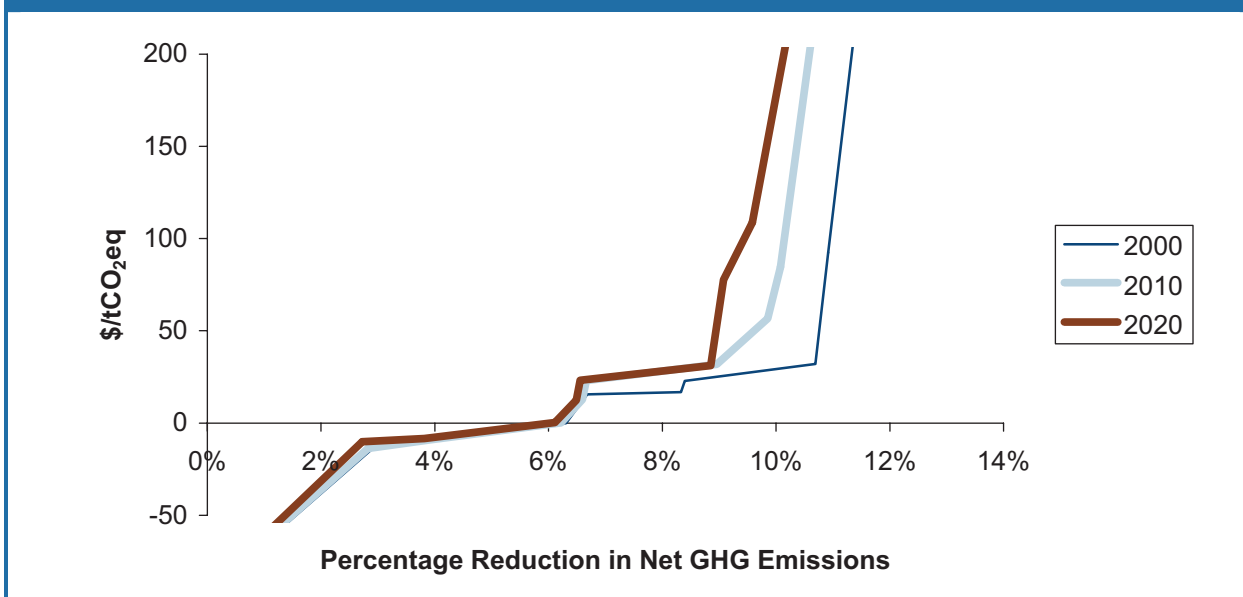


Figure 1-25: MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Production Constant, 2000–2020



reveal the importance of this assumption, because total mitigation is substantially larger at any given price when production is assumed to remain constant. For those options that increase yields, constant production can be maintained while reducing the number of livestock by an amount corresponding to the increase in productivity. These reductions in the number of livestock can have a sizable impact on emissions. With an assumption that the number of animals remains constant, emissions tend to fall less because the reductions in emissions only come from the change in emissions per animal with no change in emissions due to a change in population. Some mitigation options even increase net greenhouse gas emissions per animal but increase productivity by an even greater proportion, leading to lower emissions per unit of output. If a constant number of animals is assumed, however, then these options will lead to an increase in emissions.

V.3.5 Baselines, Mitigation Costs, and MACs for Total Agriculture

Table 1-19 presents estimates of baseline net GHG emissions from agriculture, aggregated across croplands management, rice cultivation, and livestock management by region by year used in this analysis. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-19: Baseline Emissions from All Agriculture Used in This Report (MtCO₂eq)

Country/Region	2000	2010	2020
Africa	301	364	431
Annex I	1,258	1,230	1,297
Australia/New Zealand	104	109	111
Brazil	249	292	327
China	789	791	876
Eastern Europe	86	93	99
EU-15	313	296	303
India	417	441	480
Japan	65	49	50
Mexico	57	67	85
Non-OECD Annex I	282	254	274
OECD	1,018	1,026	1,080
Russian Federation	237	201	215
South & SE Asia	1,141	842	898
United States	338	351	370
World Total	4,563	4,417	4,822

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Note: These emissions reflect the baseline emissions used in calculating agricultural mitigation.

Table 1-20 provides estimates of the percentage reduction in net GHG emissions (relative to the aggregated agricultural emissions baseline used in this analysis) that could potentially be achieved at prices between \$0/tCO₂eq and \$60/tCO₂eq for both 2010 and 2020 in major regions around the world.

Figures 1-26 and 1-27 present MACs for global agriculture, aggregated across croplands management, rice cultivation, and livestock management, for assumptions of constant area and number of animals and constant production, respectively.

Table 1-20: Total Agriculture: Percentage Reductions from Baseline at Different \$/tCO₂eq Prices

Country/Region	2010					2020				
	\$0	\$15	\$30	\$45	\$60	\$0	\$15	\$30	\$45	\$60
Africa	1.6%	3.1%	3.6%	4.5%	4.5%	1.4%	3.0%	3.5%	4.4%	4.4%
Annex I	11.1%	13.7%	18.1%	19.1%	20.0%	10.8%	13.1%	16.2%	18.9%	19.6%
Australia/New Zealand	6.7%	6.9%	9.5%	11.6%	12.4%	6.9%	7.3%	10.2%	12.1%	12.9%
Brazil	3.2%	4.5%	5.8%	5.8%	7.2%	3.1%	4.5%	5.6%	5.6%	7.0%
China	7.8%	14.2%	14.1%	14.5%	15.0%	6.3%	11.6%	12.1%	12.5%	12.9%
Eastern Europe	7.7%	9.5%	10.4%	10.7%	11.7%	7.2%	9.0%	10.3%	10.3%	10.7%
EU-15	8.1%	10.9%	13.0%	13.3%	16.4%	7.9%	10.5%	12.0%	14.0%	16.0%
India	1.6%	9.7%	9.5%	9.6%	9.7%	1.5%	9.3%	9.3%	9.3%	9.3%
Japan	2.7%	15.5%	15.6%	15.6%	15.6%	2.8%	15.5%	15.5%	15.7%	15.7%
Mexico	5.2%	6.0%	8.3%	8.3%	8.3%	5.0%	8.0%	8.0%	8.0%	8.0%
Non-OECD Annex I	15.0%	15.0%	24.4%	24.5%	24.7%	14.0%	14.0%	15.7%	22.9%	23.3%
OECD	9.5%	12.5%	15.8%	16.9%	17.9%	9.3%	12.4%	15.6%	17.0%	17.7%
Russian Federation	18.2%	18.2%	30.1%	30.2%	30.4%	17.2%	17.2%	19.3%	28.4%	28.9%
South & SE Asia	8.5%	13.3%	13.7%	16.4%	17.7%	9.2%	14.1%	14.6%	17.0%	17.2%
United States	14.2%	17.8%	22.9%	25.0%	25.0%	13.8%	16.8%	23.4%	24.9%	24.9%
World Total	7.1%	11.0%	12.5%	13.5%	14.3%	6.7%	10.4%	11.6%	13.0%	13.4%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

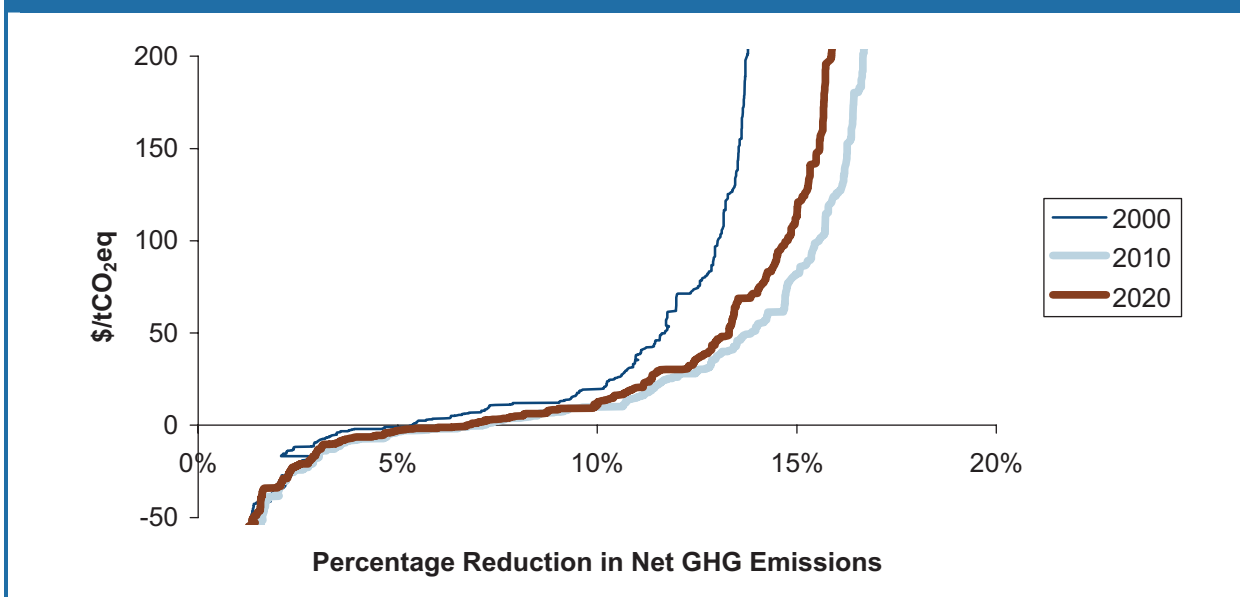
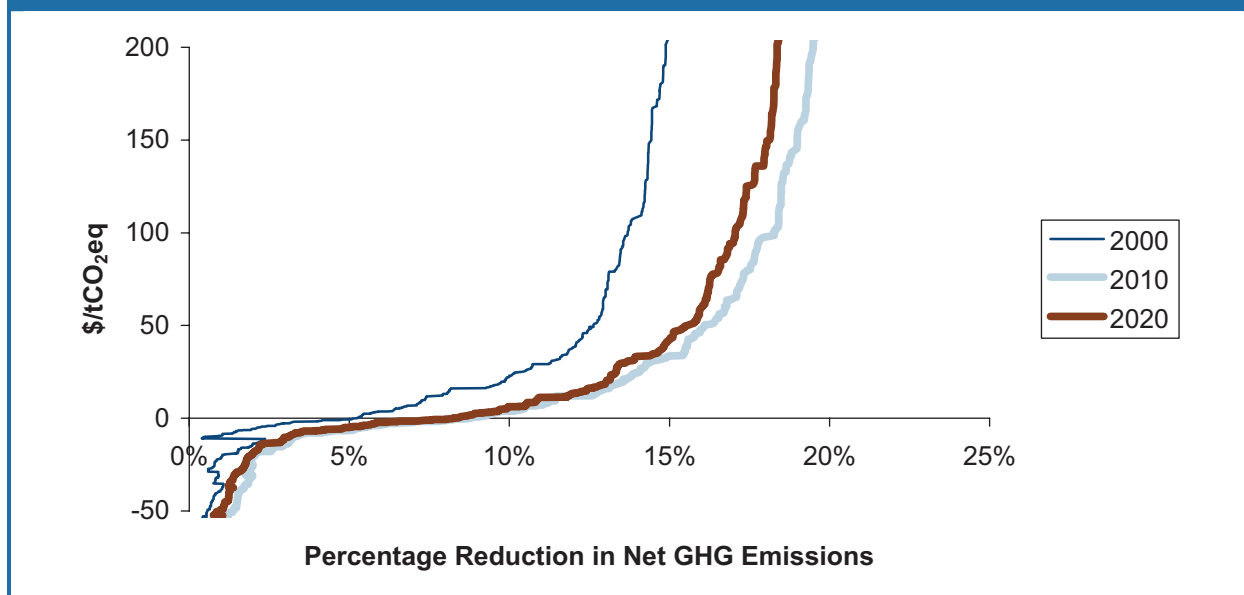
Figure 1-26: Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Area/Animals Constant, 2000–2020

Figure 1-27: Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Production Constant, 2000–2020



V.3.6 Agricultural Commodity Market Impacts of Adopting Mitigation Options: Use of the IMPACT Model

Many of the mitigation options considered for the agricultural sector have substantial impacts on agricultural productivity and/or the cost of production. As a result, any significant adoption of these options is expected to shift the market supply curves and move agricultural commodity markets to new equilibrium points. Increases in productivity will have positive supply shifts and will tend to increase market equilibrium quantity and reduce market prices, whereas increases in production costs will have the opposite effect, reducing market quantity and putting upward pressure on market prices. Thus, market equilibrium price and quantity could be either higher or lower than current and projected baseline levels, depending on the net effects of the mitigation options. Not only do these market-level impacts affect the cost of greenhouse gas mitigation, they also affect total mitigation, because emissions are generally tied to the quantity of output produced. For instance, there may be an option that reduces net greenhouse gas emissions per hectare of cropland but through broader market effects then leads to an increase in equilibrium cropland area. With a large enough increase in area, total emissions from adopting the option may actually increase because additional emissions from the larger area more than offset the reduction in emissions per hectare.

To examine the magnitude of these market-level effects in agricultural markets, IFPRI's IMPACT model is used. IMPACT models world supply and demand for agricultural products for 36 world regions, as well as trade between regions. The model is capable of incorporating shifts in supply and/or demand in one or more commodities in one or more regions and then solving for a new global equilibrium in all commodities.

For cropland and rice cultivation options, estimated percentage changes in yield (kg/hectare) and percentage changes in production costs per unit of output (\$/metric ton) for each mitigation option were provided as inputs to the IMPACT model. Similarly, percentage changes in milk or meat production per

animal (kg/head) and production costs per unit of output (\$/metric ton) estimated for each enteric fermentation option were provided as inputs to IMPACT. Manure management greenhouse gas mitigation options were assumed to have no impact on livestock productivity and were not run through the IMPACT model.

Applying the percentage changes in productivity and costs implied by the mitigation options to the baseline levels of these variables in the IMPACT model, the model moves to a new equilibrium. The values for key variables in the baseline and mitigation scenario are then compared to determine the incremental impacts of adopting the mitigation option. Mitigation options are run through the model independently from other options, but each option is applied simultaneously to all regions where that option was believed to be feasible.

Two illustrative examples are presented to show the market adjustments being captured in the IMPACT model and the influence of those adjustments on the abatement curves. The first examines the effects of global adoption of the antimethanogen vaccine option on beef, dairy, and sheep and goat meat markets relative to baseline values. As shown in Figure 1-28, world prices are reduced for all three of the primary livestock categories that may adopt this mitigation option, with reductions ranging from about 4 percent to 9 percent. Figure 1-29 presents the effects on global production, where production increases by 2 percent to 4 percent for each product. In Figure 1-30, the impacts on global animal numbers are shown. The IMPACT model estimates reductions in the number of animals of approximately 0.5 percent to 2 percent for each livestock category included. These changes in prices, production, and animal numbers are attributable to the increase in productivity associated with this option. Although there are costs of purchasing and administering the vaccine, the increase in productivity more than offsets these costs in most regions, leading to more production from fewer animals. The resulting positive supply shift decreases equilibrium market price.

Figure 1-28: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on World Prices Using the IMPACT Model

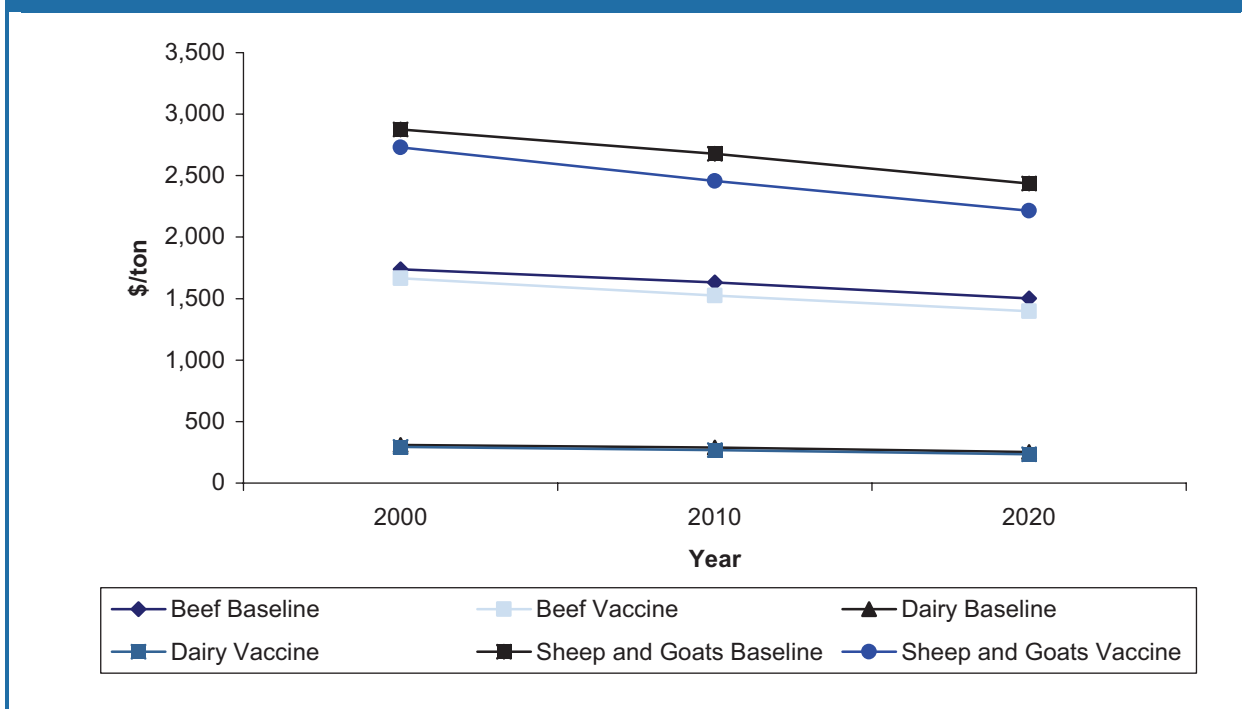


Figure 1-29: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Production Using the IMPACT Model

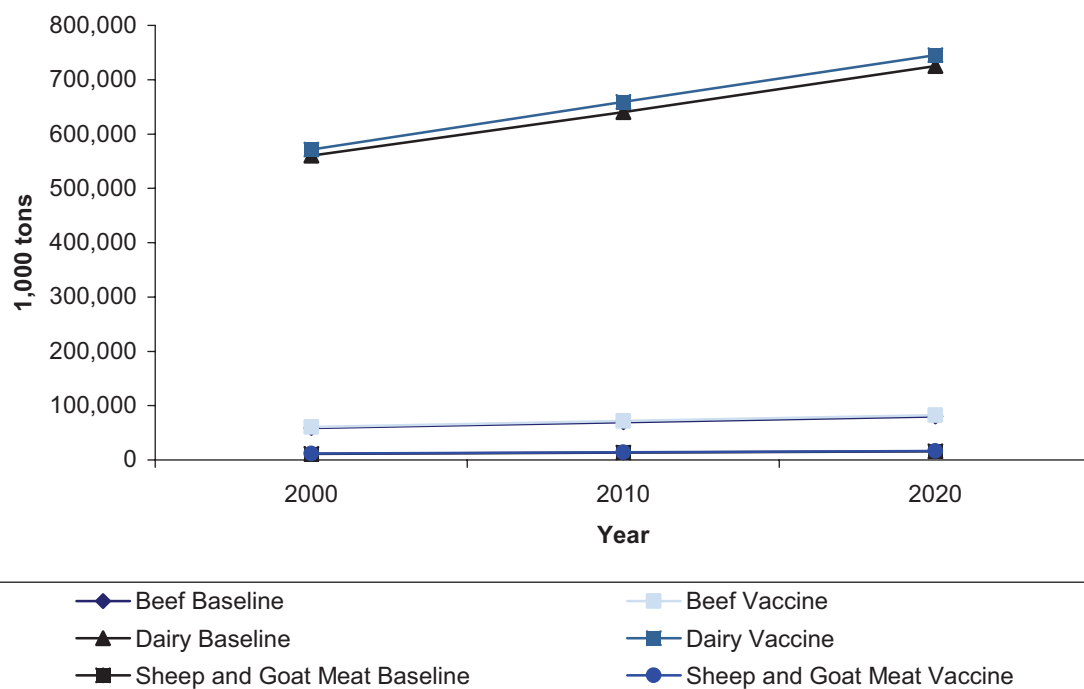
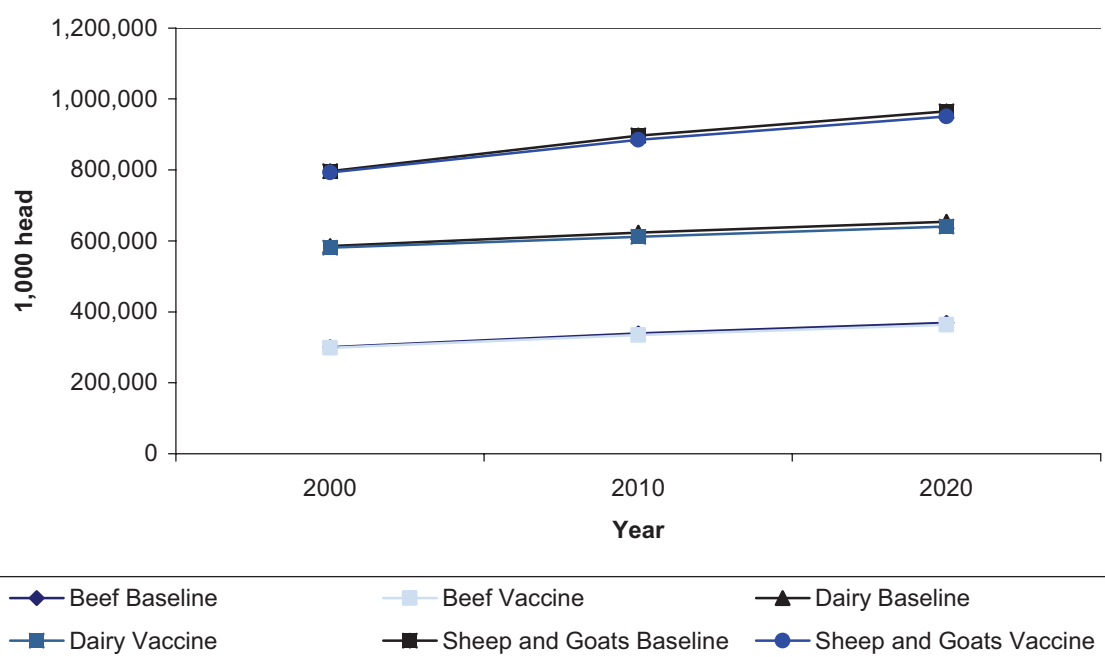


Figure 1-30: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Number of Animals Using the IMPACT Model



The second example simulates the effects of global adoption of the shallow flooding mitigation option on rice markets relative to baseline values. The shallow flooding option is expected to result in both reduced emissions and higher productivity. As shown in Figure 1-31, the global price of rice is reduced, with reductions ranging from about 3 percent to 10 percent. Figure 1-32 presents the effects on global rice production, where production increases by 1 percent to 2.5 percent. In Figure 1-33, the impact on global rice area is shown, with the IMPACT model estimating acreage reductions between 0.3 to 1 percent. Similar to the antimethanogen vaccine option examined above, this option results in an increase in productivity, which results in more production from less area. The positive supply shift leads to a decrease in equilibrium market price.

These market-level changes in area, production, and price are then incorporated into the MAC to examine the sensitivity of the MACs to inclusion of market effects. These effects are potentially very important because many options will have an effect on equilibrium prices and quantities if widely adopted, which will affect the cost of mitigation, as well as total mitigation achieved. However, the engineering approach used in this report is unable to capture feedbacks from changing market conditions. For comparison purposes, the MAC curves without market adjustments are recalculated with full adoption of a single option being analyzed to be consistent with the MACs calculated using IMPACT model results.

Figure 1-34 compares net GHG abatement under global adoption of the antimethanogen vaccine calculated three different ways: 1) with the number of animals held constant, 2) with production of the relevant commodities held constant, and 3) allowing both number of animals and production to vary, as well as reflecting other market adjustments simulated using the IMPACT model. Mitigation with production held constant is much greater than with the number of animals held constant because this is an option that increases productivity. Thus, the same production level can be achieved with fewer animals, which provides additional emissions reductions on top of the reduction in emissions per animal associated with the option. Incorporating market adjustments results in a price decrease, which leads to reduced incentives for investment and production in the livestock sector than if price were constant. Thus, the increase in production is smaller than for the constant number of animals case. Because there is an increase in production under the market adjustments scenario, the reduction in number of animals is smaller than for the constant production case. In addition, there are shifts in production regions and trade patterns, though the changes are relatively small for this particular option.

Similarly, Figure 1-35 compares net GHG abatement under global adoption of the shallow flooding mitigation option: 1) with rice area held constant, 2) with rice production held constant, and 3) allowing both area and production to vary, as well as reflecting other market adjustments simulated by the IMPACT model. Mitigation is similar with area held constant and production held constant for this option because the yield changes are relatively small, causing less differentiation between calculation method. The global curve with market adjustments is similar to the area constant and production constant curves other than at very low and very high prices. However, there are differences in the regions estimated to provide mitigation at different price levels depending on the abatement cost calculation method. Because there are larger differences in estimated yield changes between regions, there are more substantial shifts in production regions and trade patterns than for the antimethanogen vaccine option considered above.

Figure 1-31: Effect of Global Adoption of the Shallow Flooding Mitigation Option on World Prices Using the IMPACT Model

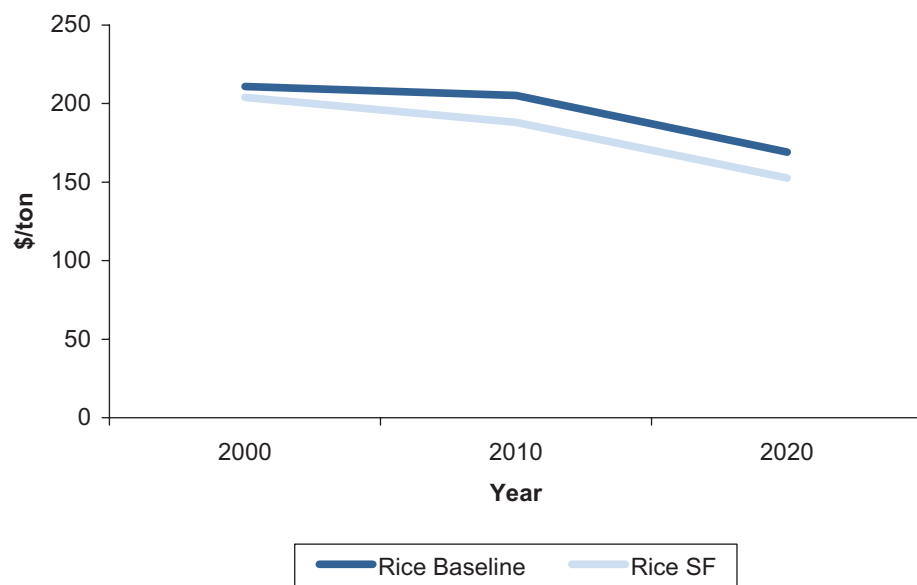


Figure 1-32: Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Production Using the IMPACT Model

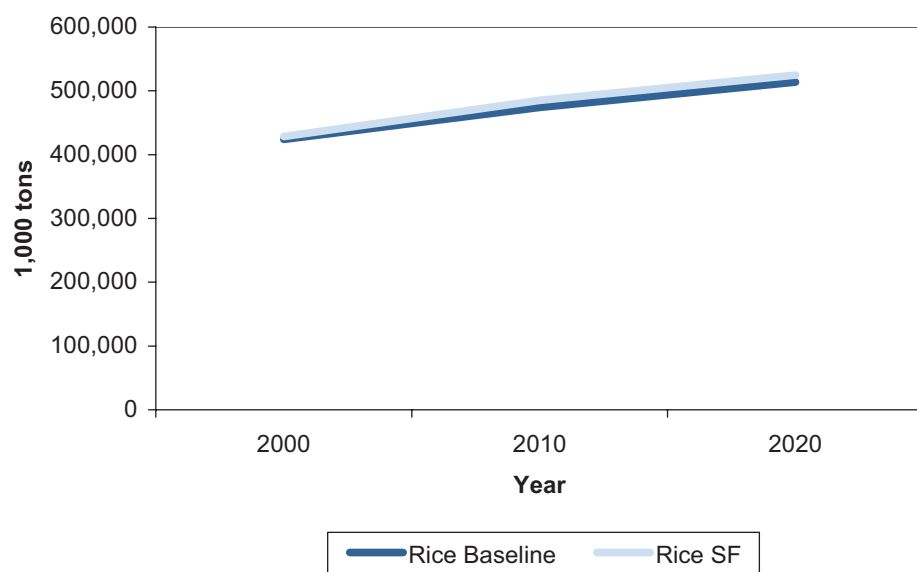


Figure 1-33: Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Rice Area Using the IMPACT Model

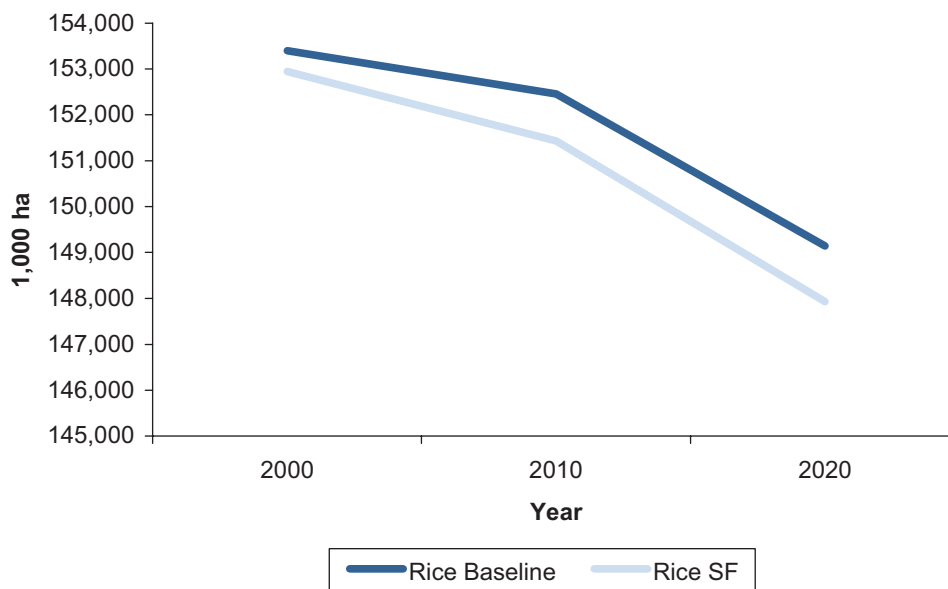


Figure 1-34: Net GHG Abatement under Global Adoption of the Antimethanogen Vaccine Option with Number of Cattle Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010

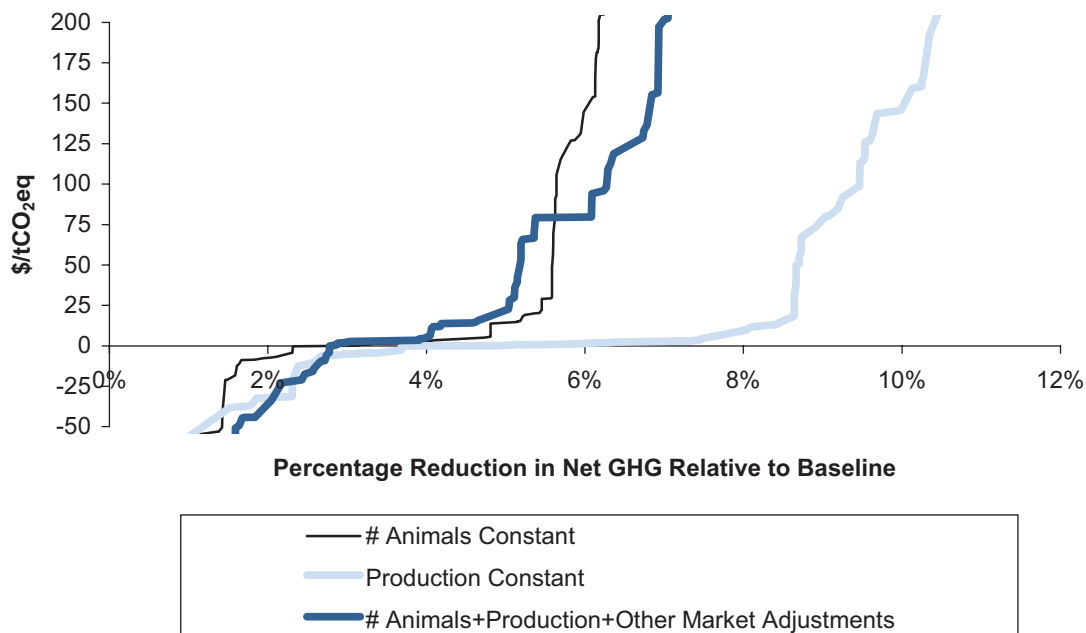
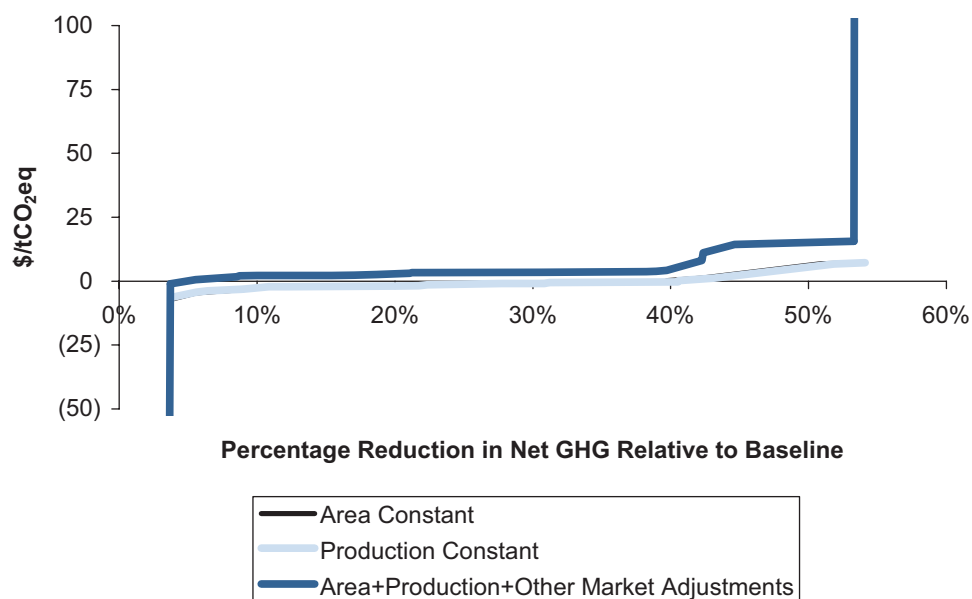


Figure 1-35: Comparison of Net GHG Abatement from Rice Cultivation under Global Adoption of the Shallow Flooding Mitigation Option with Area Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010



V.4 Conclusions

The agricultural sector generates the largest share of global non-CO₂ greenhouse gas emissions and a significant share of total global greenhouse gas emissions. Emissions in this sector are projected to increase significantly over the foreseeable future, especially in developing countries. Mitigation options to abate agricultural non-CO₂ emissions have been identified in the literature for most significant sources. This report uses a number of data sources, analytic tools, and modeling approaches to compile and estimate baseline emissions of the most significant world agricultural non-CO₂ sources and to estimate the costs of the technical mitigation potential for key regions and world totals. This report makes no explicit assumption about the policy mechanisms that might be required for adopting the mitigation options in different regions.

Cost estimates are feasible for most greenhouse gas mitigation options in the agricultural sector. This report uses an engineering bottom-up approach to estimate the \$/tCO₂eq of each mitigation option in different regions, over different time periods, by including most key elements that affect cost: net greenhouse gas effects, changes in crop yield or livestock productivity, regionally specific agricultural commodity prices, capital and input costs required to implement the mitigation option, and changes in labor requirements. The quality of data and tools used for these input parameters varies by region and by agricultural emissions category.

At the globally aggregated scale (including all regions and all non-CO₂ sources), the technical potential to mitigate non-CO₂ greenhouse gases from agriculture appears significant but not overwhelming in percentage terms. At roughly zero costs (where the benefits of implementing the mitigation options compensate for the costs of doing so), approximately 10 percent of global agricultural non-CO₂ emissions can be mitigated. At very high costs around \$150/tCO₂eq, the technical mitigation potential at the global scale approaches 20 percent of baseline emissions. These estimated percentage reductions are larger than the previous analysis supported by the USEPA and carried out for EMF-21, but these two studies are very different; this report uses more recent baseline scenarios for livestock emissions and uses completely different approaches to estimate the baseline and mitigation scenarios from croplands and rice cultivation.

For individual emissions categories, the magnitude of net greenhouse gas mitigation potential appears significant to modest depending on region and time frame. For global cropland N₂O and soil carbon emissions, approximately 15 percent of baseline emissions can be mitigated at zero costs. At costs above \$50/tCO₂eq, the percentage reduction approaches 25 percent. Nitrification inhibitors and no-till appear the most viable mitigation options, according to the simulations with the DAYCENT model, with regard to net emissions reduction potential and yield effects. The options where baseline nitrogen fertilizers are simply reduced result in net emissions similar to baseline levels.

For Asian rice systems (representing about 90 percent of world rice emissions), close to 15 percent of net baseline emissions (CH₄, N₂O and soil carbon) can be mitigated at zero costs in years 2010 and 2020. As costs approach \$100/tCO₂eq, over 25 percent of net baseline emissions can be mitigated. Shallow flooding, ammonium sulfate, and full conversion to midseason drainage appear the most viable mitigation options, according to the simulations with the DNDC model, with regard to net emissions mitigation potential and yield effects. Upland rice almost eliminates emissions but has adverse yield effects. Shallow flooding has the additional benefit of water conservation, though water as an unpriced commodity in this context does not factor into the cost estimates.

For global livestock emissions, approximately 7 percent can be mitigated at zero costs assuming a constant number of animals, whereas roughly 9 percent can be mitigated assuming a constant level of

production. As costs approach \$125/tCO₂eq, the technical mitigation potential reaches 16 and 18 percent of baseline emissions, when, respectively, constant number of animals and constant production are assumed. There are somewhat surprisingly few large differences among the mitigation options in terms of their non-CO₂ mitigation potential at the global scale relative to baseline levels.

Many mitigation options have negative costs and it is difficult to assess whether important costs have been omitted or if barriers to adoption exist that are not accounted for. High-cost options tend to be those that are either not very effective at reducing net greenhouse gases or that have adverse yield and productivity effects. Adoption barriers have not been explicitly addressed (all mitigation options considered technically feasible in a given region are assumed to be adopted in data year 2000). Accounting for adoption barriers to gain a more complete picture of greenhouse gas mitigation potential is an important area for future research.

Consideration of net greenhouse gas effects (CH₄, N₂O, and soil carbon) is particularly important in the agricultural sector to evaluate the effectiveness of different mitigation options. This is especially true for croplands and rice cultivation. In croplands, options considered *a priori* to be good candidates for reducing soil N₂O emissions (e.g., reducing baseline nitrogen application rates) led to no significant net greenhouse gas emissions reductions relative to the baseline because of offsetting soil carbon effects. Likewise with rice cultivation, some options are good CH₄-reducing strategies but increase N₂O (e.g., midseason drainage), while others have little effect on CH₄ but are good N₂O-reducing strategies (e.g., use of ammonium sulfate under certain conditions). The inclusion of fossil fuel CO₂ emissions associated with either on-farm practices or off-farm production processes, such as fertilizer production, is an additional net greenhouse gas consideration that was not included here.

The long-lasting benefits of N₂O and CH₄ reductions relative to the potentially reversible benefits of soil carbon sequestration deserve attention. In this report, there is no reversal of soil carbon sequestration due to, say, adoption of no till, because this practice is assumed to be adopted immediately and continuously through to 2020.

Estimating mitigation potential of agricultural non-CO₂ emissions is challenging at the international scale given the high degree of heterogeneity in management and biophysical conditions. Use of process models like DAYCENT (for cropland emissions) and DNDC (for rice cultivation emissions) in this report can help capture this variability and improve confidence in net greenhouse gas and yield estimates. Use of these models at such large scales is intended to show the general trends between baseline and mitigation scenarios, while adequately capturing heterogeneous effects. These models are not intended to match small-scale (e.g., farm scale) conditions over the entire regions to which they are being applied.

Livestock baseline emissions are taken from USEPA (2006), which for many regions relies on IPCC Tier I default methodologies. Mitigation studies found in the literature are applied to those baselines. This approach raises two key issues that need to be addressed in future work: 1) the identification of more detailed baseline management activities so that there is more certainty about the implications of adopting the mitigation options and 2) the suitability of applying mitigation options to regions outside of an original case study area.

Adoption of the mitigation options in this report would lead to agricultural commodity effects and therefore would affect baseline commodity prices, crop area, production levels of crops, and livestock populations and livestock products. These changes in turn change greenhouse gas levels and thus the effectiveness of the mitigation options. The agricultural market sensitivity experiments with the IMPACT model show this to be the case. The core mitigation estimates in this report use a static, engineering approach that is unable to capture these market dynamics. For this reason, cost estimates and marginal abatement curves are shown using either constant area (livestock population) or constant crop (livestock)

production. For the livestock sector, where many mitigation options actually increase emissions per animal, it is particularly important to show the implications of both approaches; using constant livestock production, as expected, leads to greater emissions reduction estimates. Fuller representation of these market feedbacks for future global agricultural mitigation analyses will be important.

Additional research is also necessary to identify which mitigation options are best suited for different regions and subregions and what kind of adoption barriers different mitigation options may face. This report excludes some options from being applied in certain regions, but further refinement is required.

Finally, anthropogenic climate change is not considered in this report for the 2000 to 2020 period but could affect future agricultural baseline emissions and thus mitigation potential. Anthropogenic climate change will become a more important issue for analyses that look beyond 2020.

V.5 References

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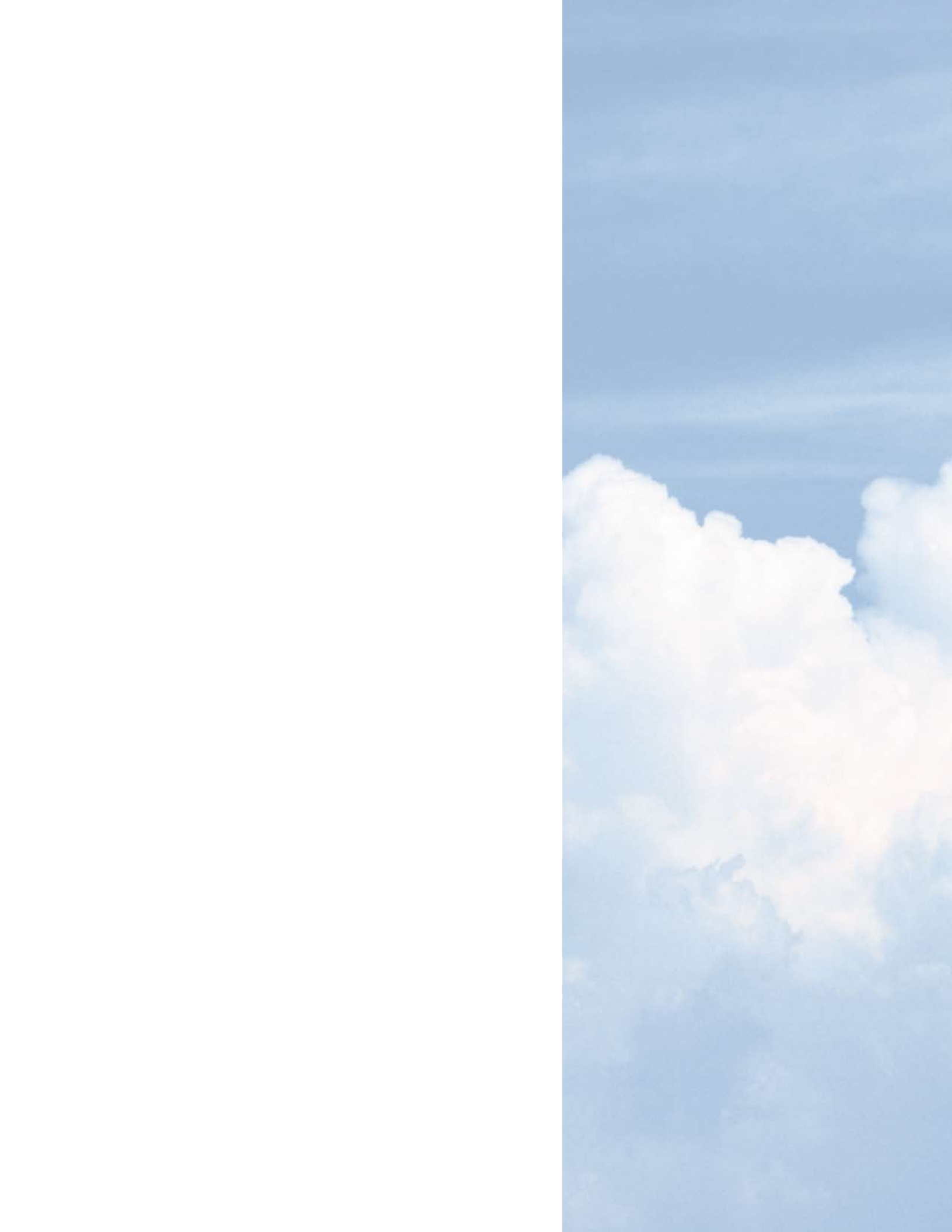
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Section V: Agriculture Sector Appendixes

Appendixes for this section are available for download from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.





Global Mitigation of Non-CO₂ Greenhouse Gases



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