Appendix A: Additional Information to Technical Summary

A.1 MACs by Sector

The MACs generated as a result of this analysis are available online at the **USEPA's Non-CO_2 Gases Economic Analysis and Inventory** Web site, under the International Analyses Section. The Web address is <http:/www.epa.gov/nonco2/econ-inv/international.html>.

The Web site provides links to the major sources for which abatement cost data are available and allows you to download a group of zipped spreadsheets for each sector. Below is a list of the files that should be unzipped for the coal sector. The other sectors have the same file types and follow the same naming convention.

1. MAC_Coal_tCO_2eq.xls. Reports methane reference emissions and MAC data in absolute reductions in million metric tons of carbon dioxide equivalent (MtCO_2eq) in the coal sector using a USD per ton of carbon equivalent (\$/tCO_2eq) scale.
2. MAC_Coal_%tCO_2eq.xls. Reports MAC data in percentage reductions from the reference baseline in MtCO_2eq in the coal sector using a \$/tCO_2eq scale.
3. MAC_Coal_CH4.xls. Reports methane reference emissions and MAC data in absolute reductions in Gigagrams (Gg) of methane in the coal sector using a USD per ton of methane (\$/tCH_4) scale.
4. MAC_Coal_%tCH4.xls. Reports MAC data in percentage reductions from the reference baseline in Gg of methane in the coal sector using a \$/tCH_4 scale.

A.2 Energy Modeling Forum Working Group 21 (EMF-21) Countries by Region

Table A-1 presents the regional grouping of countries used in this report to remain consistent with the EMF-21 study's regional MAC analyses.

Table A-1: EMF Regional Country Groups

Africa	**Annex I**	**Australia/New Zealand**	**Brazil**
Algeria	Australia	Australia	Brazil
Angola	Austria	New Zealand	
Benin	Belarus		
Botswana	Belgium		
Burkina Faso	Bulgaria	**Canada**	**China**
Burundi	Canada		
Cameroon	Croatia	Canada	China
Cape Verde	Czech Republic		Hong Kong, China
Central African Republic	Denmark		Macao, China
Chad	Estonia		
Comoros	Finland		
Congo, Dem. Rep.	France		

(continued)

Table A-1: EMF Regional Country Groups (continued)

Africa (continued)	Annex I (continued)	CIS	Eastern Europe
Congo, Rep. (Kinshasa)	Germany	Armenia	Albania
Cote d'Ivoire	Greece	Azerbaijan	Bosnia and Herzegovina
Djibouti	Hungary	Belarus	Bulgaria
Egypt, Arab Rep.	Iceland	Georgia	Croatia
Equatorial Guinea	Ireland	Kazakhstan	Czech Republic
Eritrea	Italy	Kyrgyz Republic	Estonia
Ethiopia	Japan	Moldova	Hungary
Gabon	Latvia	Tajikistan	Latvia
Gambia, The	Liechtenstein	Turkmenistan	Lithuania
Ghana	Lithuania	Uzbekistan	Macedonia, FYR
Guinea	Luxembourg		Poland
Guinea-Bissau	Monaco		Romania
Kenya	Netherlands	**EU-15**	Slovak Republic
Lesotho	New Zealand		Slovenia
Liberia	Norway	Austria	Yugoslavia, FR (Serbia/Montenegro)
Libya	Poland	Belgium	
Madagascar	Portugal	Denmark	
Malawi	Romania	Finland	**India**
Mali	Russian Federation	France	
Mauritania	Slovak Republic	Germany	India
Mauritius	Slovenia	Greece	
Mayotte	Spain	Ireland	
Morocco	Sweden	Italy	**Japan**
Mozambique	Switzerland	Luxembourg	
Namibia	Turkey	Netherlands	Japan
Niger	Ukraine	Portugal	
Nigeria	United Kingdom	Spain	
Rwanda	United States	Sweden	**Korea, Republic**
Sao Tome and Principe		United Kingdom	
Senegal			Korea, Republic (South)
Sierra Leone			
Somalia			
South Africa			
Sudan			
Swaziland			
Tanzania			
Togo			
Tunisia			
Uganda			
Zambia			
Zimbabwe			

(continued)

Table A-1: EMF Regional Country Groups (continued)

Latin America/ Caribbean	Mexico	Middle East	Non-EU Europe
Antigua and Barbuda	Mexico	Bahrain	Andorra
Argentina		Iran, Islamic Rep.	Channel Islands
Aruba		Iraq	Cyprus
Bahamas, The	**Non-OECD Annex I**	Israel	Faeroe Islands
Barbados		Jordan	Greenland
Belize	Belarus	Kuwait	Iceland
Bermuda	Bulgaria	Lebanon	Isle of Man
Bolivia	Croatia	Oman	Liechtenstein
Cayman Islands	Estonia	Qatar	Malta
Chile	Latvia	Saudi Arabia	Monaco
Colombia	Liechtenstein	Syrian Arab Republic	Norway
Costa Rica	Lithuania	United Arab Emirates	San Marino
Cuba	Monaco	West Bank and Gaza	Switzerland
Dominica	Romania	Yemen, Rep.	
Dominican Republic	Russian Federation		
Ecuador	Slovenia		
El Salvador	Ukraine		
Grenada			
Guatemala			
Guyana			
Haiti			
Honduras			
Jamaica			
Marshall Islands			
Netherlands Antilles			
Nicaragua			
Panama			
Paraguay			
Peru			
Puerto Rico			
St. Kitts and Nevis			
St. Lucia			
St. Vincent and the Grenadines			
Suriname			
Trinidad and Tobago			
Uruguay			
Venezuela			

(continued)

Table A-1: EMF Regional Country Groups (continued)

OECD	**OPEC**	**Russian Federation**	**South & SE Asia**
Australia	Algeria	Russian Federation	Afghanistan
Austria	Indonesia		American Samoa
Belgium	Iran, Islamic Rep.		Bangladesh
Canada	Iraq	**Turkey**	Bhutan
Czech Republic	Kuwait		Brunei
Denmark	Libya	Turkey	Cambodia
Finland	Nigeria		Fiji
France	Qatar		French Polynesia
Germany	Saudi Arabia	**Ukraine**	Guam
Greece	United Arab Emirates		Indonesia
Hungary	Venezuela	Ukraine	Kiribati
Iceland			Korea, Dem. Rep. (North)
Ireland			Lao PDR
Italy		**USA**	Malaysia
Japan			Maldives
Korea, Rep. (South)		United States	Micronesia, Fed. Sts.
Luxembourg		Virgin Islands (U.S.)	Mongolia
Mexico			Myanmar
Netherlands			Nepal
New Zealand			New Caledonia
Norway			Northern Mariana Islands
Poland			Pakistan
Portugal			Palau
Slovak Republic			Papua New Guinea
Spain			Philippines
Sweden			Samoa
Switzerland			Seychelles
Turkey			Singapore
United Kingdom			Solomon Islands
United States			Sri Lanka
			Thailand
			Tonga
			Vanuatu
			Vietnam

CIS = Commonwealth of Independent States; EU = European Union; OECD = Organisation of Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Appendix B: Coal Mining Sector—Incorporating Technology Change to MAC Analysis

This appendix provides an overview of recent efforts to account for limitations in the EMF-21 MAC analysis by introducing a new framework that accounts for technology changes in coal mining CH_4 mitigation options. In the following discussion we present the methodology for incorporating technology change and develop revised MACs for 2000, 2010, and 2020. We present the results of our analysis for four major emitting countries: the United States, the Russian Federation, Poland, and China, and we include sensitivity analysis to key technology change assumptions used.

This analysis also explicitly models changes in input costs, productivity, and reduction efficiency of abatement options over time. One-time capital costs and O&M costs are broken into their factor inputs (i.e., capital, materials, labor and energy) so that individual technology trends (i.e., changes in prices and productivity) can be applied. Changes in these input factors are expressed in terms of the annual percentage change in price and productivity. Price trends reflect changes in production/input costs, and productivity trends reflect advances in technologies and processes that make constant levels of production possible with fewer inputs. The price and productivity trends over time are then used to adjust one-time capital costs and O&M costs, which in turn affect the economic viability of the option (i.e., the breakeven price). For additional details on the technical change methodology, see Gallaher and Delhotal (2005).

B.1 Mine-Level Data

Previous analysis has been static, based on current average costs applied to a single representative firm. This analysis goes beyond the previous studies and incorporates mine-level data and employs a framework for adjusting MACs to account for technical enhancements and decreasing costs of abatement over time.

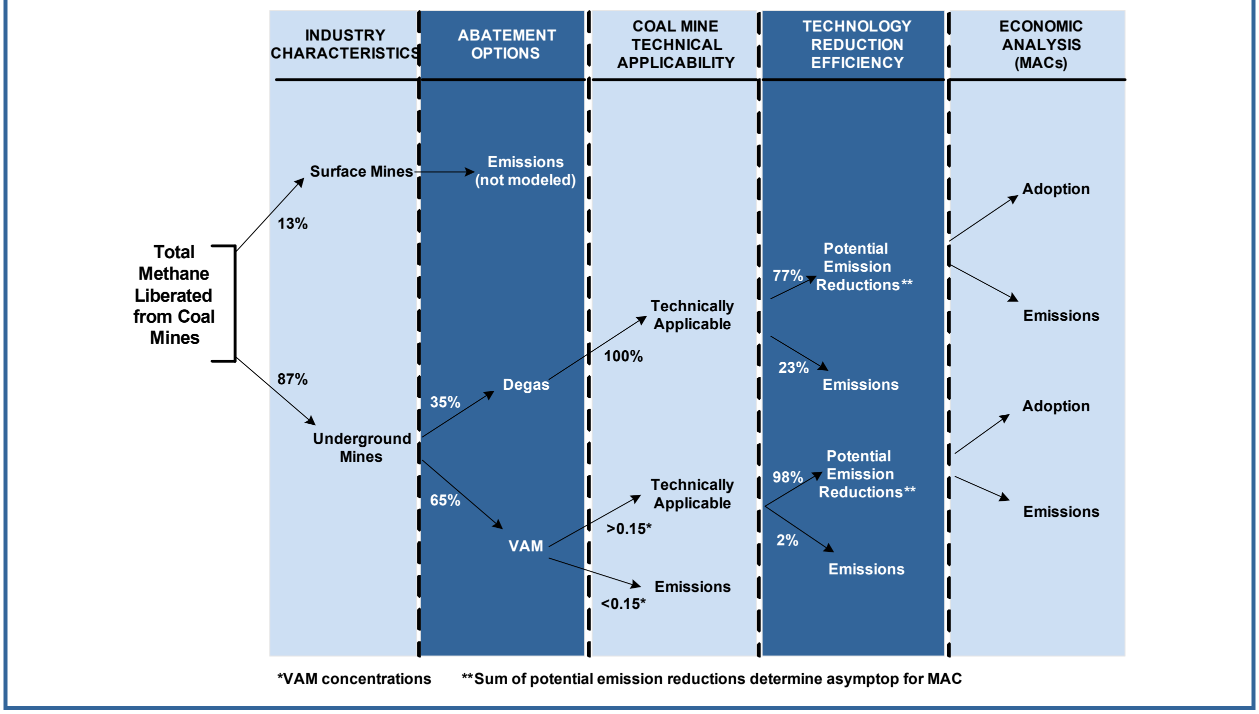
Information was available on 56 underground U.S. coal mines for 2000. These 56 mines accounted for 75 percent of the total liberated CH_4 associated with U.S. coal production. Engineering costs for each abatement option were calculated based on individual mine characteristics, such as annual mine production, gassiness of the coal deposits, and CH_4 concentration in ventilation flows. Detailed engineering cost information was unavailable for non-U.S. underground coal mines. Thus, for non-U.S. mines, costs were estimated as a function of mine production and liberated CH_4.

B.2 Adjustment Factors Used in Coal Mining Technology Analysis

Figure B-1 summarizes the key parameters that determine the share of CH_4 emissions that can be captured as a function of individual mine and technology characteristics. Note that the technical potential defines the vertical asymptote of the MAC. The technical potential can change over time when any of the following occurs:

- baseline emissions change;
- mine characteristics change, including the relative number of underground versus surface mines and the maximum percentage of CH_4 that can be liberated and recovered via premine drilling (i.e., degasification);

Figure B-1: Key Parameters in Coal Mine Model



Note: The asymptote refers to the MAC approaching a limit of total potential reductions. The curve goes inelastic at a given point because of the engineering limitations of current technologies.

- limitations of VAM technology are overcome (e.g., current technologies require CH_4 concentration greater than 0.15 percent); and
- reduction efficiency of degasification and VAM technologies increases (i.e., the share of CH_4 abated versus emitted).

All of these factors will potentially change over time as a result of enhancements to existing technologies or introduction of new processes and procedures. For example, in the United States, advances in surface mining are projected to decrease underground mining activities, reducing the technical potential for CH_4 abatement. Also, VAM technology is projected to improve during the next 20 years, decreasing the technical applicability concentration level below 0.15 percent CH_4. Table B-1 provides the assumptions affecting technical potential over time, in addition to the general price and productivity trends that influence capital and annual costs (described in the introduction to Section IV).

Table B-1: Trends Affecting Technical Potential over Time for Coal Mines

Trend	Actual (2000)	Projected (2020)
Share of coal production from underground mines	8.007%	79.00%
Percentage of total CH_4 liberated by degasification (versus liberated through mine shafts)	36.00%	38.00%
Technical applicability for VAM: lowest feasible CH_4 concentration	0.15%	0.10%
Reduction efficiency for degasification	77.00%	84.00%
Reduction efficiency for VAM	97.00%	98.00%

Note: Trends are used for all mines globally and are based on expert judgment. They are not intended to represent official analysis by the USEPA.

B.2.1 Share of Domestically Supplied Factors of Production for Coal Mine Options

In developing countries, the shift toward domestically supplied inputs will result in a reduction in the cost of implementing the abatement technology. For example, China currently relies on capital and material imported from the United States, EU-15, and Japan. As technology and information is transferred over time, China will shift away from imported factors of production and begin to supply the required capital and material domestically, which will make more abatement options economically viable.

The initial share of domestically supplied factors of production is estimated based on the relative maturity of the coal mining industry and the technology intensity in each country. Table B-2 shows domestic input shares for China in 2000 and 2020.

Table B-2: Share of Domestic Inputs for Chinese Coal Mine Abatement Options

Input	2000 (Estimate)	2020 (Projection)
Domestic share of labor	75%	92%
Domestic share of capital	0%	53%
Domestic share of materials	50%	75%

B.3 Results

Applying the cost analysis and trends described above, we developed shifts in the MACs for selected countries for 10-year intervals from 2000 to 2020. Several of the MACs are discussed below to highlight the factors underlying the shifts in the curves.

B.3.1 Data Tables and Graphs

Figures B-2 and B-3 show estimated MACs for 2000, 2010, and 2020 for U.S. and Chinese coal mining sectors, accounting for technology change over time. The magnitude of the shifts reflects both changes in abatement technologies and trends in the share of underground versus surface mining. For example, after 2020, the shift in the U.S. MACs slows because underground mine production is projected to decrease slightly. However, technology improvements continue, driving down costs and subsequently increasing the adoption of abatement options.

Table B-3 summarizes the factors driving the shifts in the MACs for the coal mining sector in terms of percentage changes from 2000 to 2020. Over time, the cost of abatement options decreases while the options' reduction efficiency increases. These factors combine to increase economic viability of the mitigation options, hence lowering their breakeven price and shifting the MACs downward. As shown in Table B-3, the change in reduction efficiency is technology specific and assumed to be constant across countries, increasing, on average, to 10 percent by 2020.

However, changes in costs vary greatly across each country because of the changing shares of domestic versus foreign inputs over time. China, the Russian Federation, and Poland have greater decreases in costs because they are currently importing most inputs, but they are projected to increase the use of significantly lower-cost domestic capital, labor, and materials over time. This can be seen in the MACs, resulting in greater downward shifts in these countries' curves over time relative to the United States. The changes in costs are also a function of each country's relative prices. For example, the

Figure B-2: Shift in the U.S. MAC for the Coal Mining Sector, 2000, 2010, and 2020

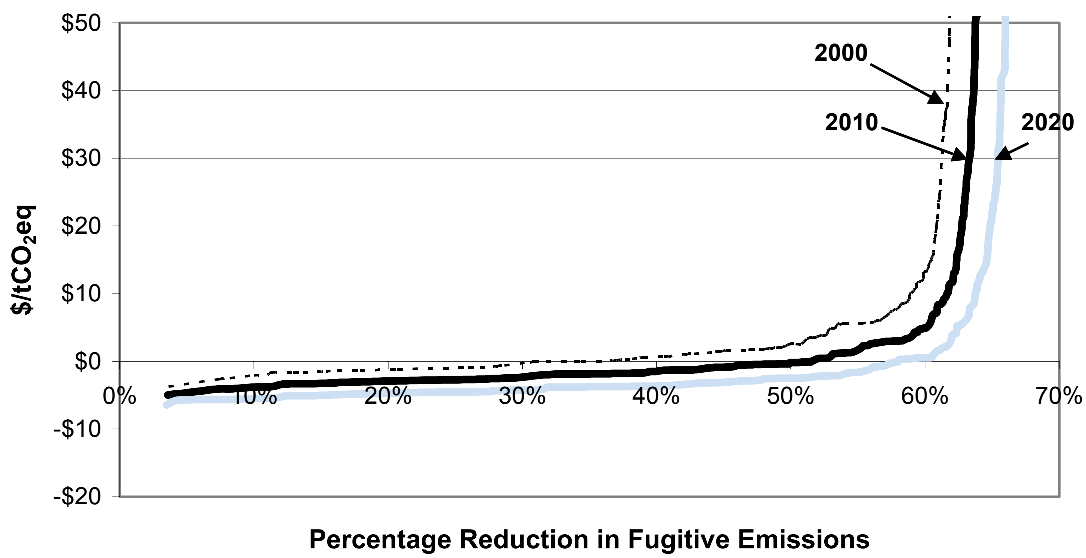


Figure B-3: Shift in China's MAC for Coal Mining, 2000, 2010, and 2020

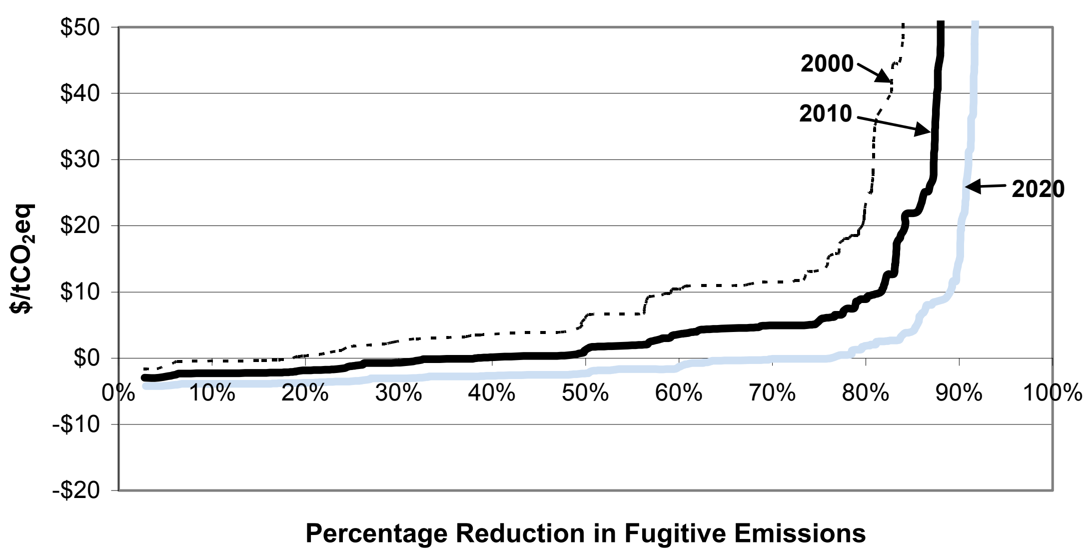


Table B-3: Percentage Change from 2000 to 2020 in Key Factors Affecting Coal Mining MACs

Country	Change in One-Time-Costs	Change in Annual Costs	Change in Reduction Efficiency
United States	37%	9%	10%
China	69%	60%	10%
Russian Federation	72%	36%	10%
Poland	74%	27%	10%

percentage change in annual costs is not as great in the Russian Federation and Poland as in China, because China has lower wages and therefore experiences a greater decrease in annual costs when switching to domestic labor.

B.3.2 Sensitivity Analyses

The MACs presented in Figures B-2 and B-3 are the result of simultaneously applying several technology feasibility, efficiency, and import trends. Each trend contributes to lowering the cost and/or increasing the benefits associated with abatement technologies, and hence shifts the MACs. Sensitivity analysis was conducted to investigate which trends have the most significant impact on the MACs over time. Two scenarios are modeled for the development of Chinese MACs for coal mines: the first focuses on the rate of change in the technical applicability and reduction efficiency of abatement technologies, and the second focuses on the share of domestic versus foreign labor, capital, and materials used in the mitigation options. Table B-4 presents the lower and upper bounds used in the sensitivity analysis for the two scenarios.

Table B-4: Trends Affecting Technical Potential over Time for Chinese Coal Mines

Trend	2000	2020		
		Lower Bound	Original Projection	Upper Bound
Scenario 1:				
Technical applicability for VAM	0.15%	0.12%	0.10%	0.08%
Reduction efficiency degasification	77.00%	80.00%	84.00%	97.00%
Reduction efficiency VAM	97.00%	97.00%	98.00%	98.50%
Scenario 2:				
Domestic share of labor	75.00%	87.00%	92.00%	92.00%
Domestic share of capital	0.00%	27.00%	53.00%	67.00%
Domestic share of materials	50.00%	63.00%	75.00%	83.00%

The sensitivity analysis for Scenario 1 (technical applicability and efficiency) in the year 2020 is presented in Figure B-4. The lower and upper bounds are shown as a range for the shifts of the MAC. Similarly, Figure B-5 presents the lower and upper bounds for the sensitivity analysis for Scenario 2 (the share of domestic inputs). The two sensitivity scenarios indicate that the MACs are more sensitive to the projected trends in the share of domestic inputs and less sensitive to projected changes in technical applicability and reduction efficiency. This result is due to the abundant availability of low-wage labor in China and the relative maturity of abatement technologies for coal production (see explanatory note 1).

Figure B-4: Sensitivity Analysis for China Coal Mining 2020: Scenario 1

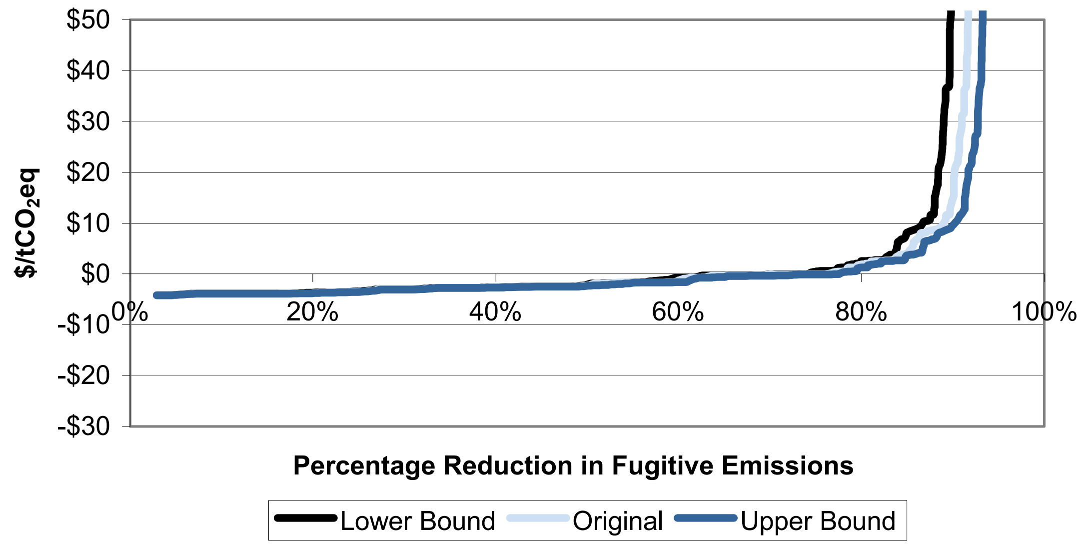
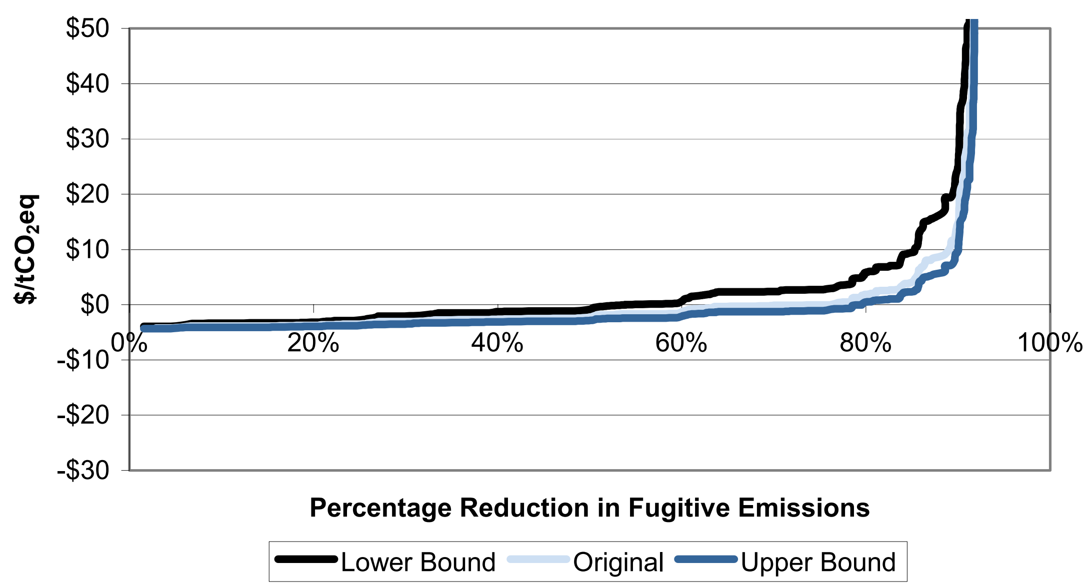


Figure B-5: Sensitivity Analysis for China Coal Mining 2020: Scenario 2



B.4 Summary and Analysis

The methodology and data discussed in this section describe the integration of technical change with mine-level data to estimate MACs for 2010 and 2020. MACs are generated for the coal mining sector for the United States, China, the Russian Federation, and Poland. These estimates represent an improvement over previously published MACs for two primary reasons. First, the mine-level data smooth out the stepwise function (based on representative entities), and second, the curves are shifted over time to account for technical change. The methodology is also applicable for projecting MACs through 2050 and 2100. However, data constraints become increasingly problematic as the time horizon increases.

The inclusion of technical change in MACs over time is important because it provides researchers and policy makers with insights into more accurate behavioral responses to potential future carbon prices. For example, MACs illustrate how the adoption of abatement technologies becomes more attractive—through decreased costs and increased benefits—as a result of changes over time in technical applicability and reduction efficiency, as well as in the share of domestic versus foreign inputs. As new technologies are adopted, MACs shift downward, potentially increasing technology adoption at any given carbon price.

B.5 Additional Information Used in Technology Change Analysis

Table B-5 details the historical data for underground coal mining production in selected countries. These data are used to determine and project emissions factors for each country.

Table B-5: Historical Coal Production for Selected Regions

Region	1990	1995	2000	2001	2002
North America	1,010	1,021	1,054	1,105	1,070
Central and South America	30	35	52	56	58
Western Europe	792	504	447	453	445
Eastern Europe and FSU	1,211	780	697	716	693
Africa	182	213	232	233	229
Asia and Oceania	1,625	2,052	1,989	2,179	2,268
World Total	**4,851**	**4,607**	**4,472**	**4,742**	**4,765**

FSU = Former Soviet Union.

The information on coal production and CH_4 liberated from individual mines for China, the Russian Federation, and Poland was extracted from several international CH_4 reports provided by the USEPA. Information on the production of coal and CH_4 emissions in China was extracted from the USEPA report *Reducing Methane Emissions from Coal Mines in China: The Potential for Coalbed Methane Development* (USEPA, 1996a). Detailed data on a majority of the state-run mines in China account for 43 percent of the coal produced and comprised 40 percent of the CH_4 liberated by the country's mines in 1994. Data on individual mines in the Russian Federation were extracted from *Reducing Methane Emissions from Coal Mines in: A Handbook for Expanding Coalbed Methane Recovery and Use in the Kuznetsk Coal Basin* (USEPA, 1996b). The data for the Russian Federation account for almost 25 percent of total coal production and almost 40 of the CH_4 liberated from the country's coal mining operations. Data on individual mines in Poland were extracted from *Reducing Methane Emissions From Coal Mines in Poland: A Handbook for Coalbed Methane Recovery and Use in the Upper Silesian Coal Basin* (USEPA, 1995) and account for nearly 50 percent of coal production and almost 75 percent of the total CH_4 liberated within the country.

Table B-6 identifies the various components required for each of the three CH_4 recovery and use options evaluated in this analysis: degasification, enhanced degasification, and VAM technologies.

Table B-6: Components of Coal Mining Abatement Options

Cost Component	Markets	Description	Degas	Enhanced Degas	VAM
Drilling	Annual capital	Drilling is continual through the life of the mine; thus, capital costs are classified as “annual” costs. Costs are proportional to annual coal production.	√	√	
	Annual materials	Material costs for drilling are estimated based on the volume of CH_4 liberated.[a]	√	√	
	Annual labor	Annual labor costs are related to drilling.	√	√	
Compressors	One-time capital	Number of compressors is proportional to the amount of CH_4 liberated per unit time.[b]	√	√	
	Gas	Natural gas used by compressors is proportional to the amount of CH_4 liberated per unit time.	√	√	
Gathering lines	One-time capital	Costs are proportional to coal production.	√	√	
	Annual labor	Annual costs are primarily labor, related to moving the lines each year.[c]	√	√	
Other fixed costs	One-time capital	Costs are proportional to coal production. Capital costs include safety equipment, licenses, and designs.[d]	√	√	
Processing	One-time capital	Costs are proportional to both coal production and CH_4 liberated and include dehydrators and enrichment units.[e]		√	
	Annual materials	Annual costs are primarily the material used for maintenance.		√	
VAM	One-time capital	Costs are proportional to both coal production and the flow of VAM. Capital costs are primarily oxidizer units, fans, and ducts.			√
	Annual labor	Annual costs are primarily the labor associated with running the oxidizer.			√

Source: RTI International, 2003.

Degas = Degasification.

[a] Material costs are related to the development rate of mines (i.e., access to drill boreholes) or the actual amount of drilling. However, because this information was unavailable, the volume of CH_4 liberated was used as a proxy.

[b] CH_4 production levels of a typical mine site will ramp up in a stepwise fashion until a point is reached at which new wells replenish production of depleted wells and production becomes flat. Compression is added as appropriate during the increase in production.

[c] In some instances, it may cost more in labor to move in-mine gas pipelines than to install a new line and leave old lines in the workings.

[d] Other fixed costs may also include monitoring, reclamation, and gas ownership (royalties).

[e] Processing one-time capital costs are related to the gas recovery technique that is used. For example, more processing will be required for gob gas recovery than inseam.

For China, the Russian Federation, and Poland, regression analysis was used to estimate cost relationships based on the known costs for the given 56 U.S. mines as a function of coal production and/or CH_4 liberated. Individual regressions were run for each cost component/factor listed in Table B-6 (e.g., annual drilling costs, one-time compressor costs), and separate sets of regressions were run for each of the three abatement options. The coefficients were then applied to the known value of coal production and CH_4 liberated for non-U.S. mines to generate cost components for each abatement technology. Details of the regression analysis are available in Gallaher and Delhotal (2005).

Following drilling of vertical or horizontal wells, compressors extract gas from the well and push the CH_4 from the well to a centralized receiving point. Then, a satellite compressor is used to pump captured CH_4 from a centralized receiving point to a facility capable of injecting recovered CH_4 into a natural gas pipeline. At the facility, a sale compressor matches the pressure of the recovered CH_4 with the natural gas pipeline

Costs for compressors are a function of the needed horsepower to compress a volume of gas. Horsepower required varies across mines depending on the level of gassiness within the mine. Generally, wellhead compressors require much less horsepower than the satellite or sales compressors. Annual costs for compressors include regular or unscheduled maintenance and labor to manage the CH_4 recovery operations.

Gathering lines placed between wellheads and compressors carry recovered CH_4 from the wellhead to the satellite compressor and on to the facility where the gas can be injected into a natural gas pipeline.

Detailed engineering cost information was not available for Chinese underground coal mines. Thus, costs were estimated as a function of mine production and liberated CH_4, based on data obtained from the USEPA report *Reducing Methane Emissions from Coal Mines in China: The Potential for Coalbed Methane Development* (USEPA, 1996a).

B.6 References

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Explanatory Notes

1. There is projected to be virtually no surface mining activity in China through 2030, because surface mining is capital intensive and geological characteristics of coal seams in China make surface mining difficult.

Appendix C: Natural Gas Sector—Incorporating Technology Change to MAC Analysis

This appendix provides an overview of recent efforts to account for limitations in the EMF-21 MAC analyses by introducing a new framework that accounts for technology changes in coal mining CH_4 mitigation options. In the following discussion, we present the methodology for incorporating technology change and develop revised MACs for 2000, 2010, and 2020. We present the results of our analysis for five major emitting countries: the United States, the Russian Federation, Ukraine, China, and Venezuela. We also include sensitivity analysis to key technology change assumptions used in the analysis.

This analysis explicitly models changes in input costs, productivity, and reduction efficiency of abatement options over time. One-time capital costs and O&M costs are broken into their factor inputs (i.e., capital, materials, labor and energy) so that individual technology trends (changes in prices and productivity) can be applied. Changes in these input factors are expressed in terms of the annual percentage change in price and productivity. Price trends reflect changes in production/input costs, and productivity trends reflect advances in technologies and processes that make constant levels of production possible with fewer inputs. The price and productivity trends over time are then used to adjust one-time capital costs and O&M costs, which in turn affect the economic viability of the option (i.e., the breakeven price). For additional details on the technical change methodology, see Gallaher and Delhotal (2005).

C.1 Adjustment Factors Used in Natural Gas System Technology Analysis

Information on capital, materials, labor, and energy costs was not provided by the natural gas economic cost model. To obtain this information, documentation from the USEPA's *Lessons Learned from Natural Gas STAR Partners* (USEPA, 2003) and interviews with industry experts were used to develop the default distribution rules for input factor costs shown in Table C-1. Almost all of the natural gas options are labor intensive. One exception is the conversion of gas pneumatic controls to instrument air technology, for which energy costs were 67 percent of annual input costs, and the remaining 20 percent were labor and 13 percent materials. For most other options, energy costs were negligible.[1]

C.1.1 International Natural Gas Emissions Factors

The technology change framework requires individual facility and equipment emissions factors unique to each country included in the analysis. The system emissions factors presented in II.2.2.2 (Table 2-6) do not provide sufficient detail to evaluate the impacts of mitigation options by facility and equipment type. At the time of this report, detailed data were only available for the U.S. natural gas infrastructure (see Table C-2). There is significantly less information available on activity and emissions factors (i.e., the number of compressors, wells, or miles of pipeline) for natural gas systems for countries such as the Russian Federation, China, Ukraine, and Venezuela. As a result, the natural gas infrastructure

[1] Other options with energy costs included electronic monitoring systems at 5 percent of total O&M costs and portable evacuation compressors, with energy as 10 percent of annual costs.

Table C-1: Default Input Factor Shares for Natural Gas Abatement Options

Input	Capital	Labor	Materials	Energy[a]
One-time capital installation costs	40%	60%	—	—
Annual O&M costs	—	80%	20%	—
DI&M	—	80%	20%	—
Inspection with specialized equipment	—	70%	30%	—
Miscellaneous technology options	—	50%	50%	—

DI&M = Direct inspection and maintenance; O&M = Operations and maintenance.

[a] Typically not a major input for natural gas abatement options.

Table C-2: IPCC's Emissions Factor and Relative Scaling Factor

Country/Region	Emissions Type	Emissions Factor (kg/petajoule)	Relative Scaling Factor
United States and Canada	Production	71,905	1.00
	Processing, transport, and distribution	88,135	1.00
Eastern Europe and FSU (Russian Federation and Ukraine)	Production	392,800	5.46
	Processing, transport, and distribution	527,900	5.99
Other oil exporting countries (Venezuela)	Production	67,795	0.94
	Processing, transport, and distribution	228,305	2.56
Rest of the world (China)	Production	67,795	0.94
	Processing, transport, and distribution	228,305	2.56

Source: IPCC, 1996.

FSU = Former Soviet Union.

Note: This table presents the regional emissions factors published by IPCC (1996) that were applied to the countries (in parenthesis) modeled in our analysis of technical change over time. This table does not represent a complete list of the regional emissions factors reported by IPCC. For example, Western Europe is not included in this table because no Western European countries were included in our technology analysis.

for other countries is characterized using available data from the United States, in combination with international production, consumption, and total emissions values reported in the *Foreign Country Briefs*, published by USEIA (2002a, 2002b, 2002c, 2002d, 2003a, 2003b) and IPCC (1996).

The size (i.e., activity factors) of a country's infrastructure for production, processing, and transmission was estimated as a function of its natural gas production. The size of the infrastructure related to storage and distribution was estimated as a function of a country's natural gas consumption. From this estimation process, the population of facilities, equipment, and miles of pipe (i.e., activity factors) was estimated.

In addition, the age and level of maintenance of the natural gas infrastructure differs across countries. This difference is accounted for by creating country-specific scaling factors that adjust the level of "leakiness" of the natural gas system. We used selected regional emissions factors from the IPCC's *1996 Revised Guidelines* report for production and processing and for transportation and distribution. IPCC reports only two emissions factors: one factor is associated with the production segment, while the second factor represents the processing, transmission and storage, and distribution segments.

Table C-2 lists the emissions factors from the IPCC's 1996 report that were used to estimate relative scaling factors for each segment of the natural gas pipeline. The scaling factors demonstrate the estimated level of leakiness present in each country's system relative to the U.S. system. For example, the Russian

Federation's system is assumed to be six times more leaky than the U.S. system.[2] This difference could be due to differences in equipment quality, more corrosive gas moving through the natural gas system, and/or poorer quality inspection and maintenance plans.

C.1.2 Share of Domestically Supplied Factors of Production for Natural Gas Options

In developing countries, the shift toward domestically supplied inputs will result in a reduction in the cost of implementing the abatement technology. For example, China currently relies on capital and material imported from the United States, EU-15, and Japan. As technology and information are transferred, China will shift away from imported factors of production and begin to supply the required capital and material domestically. This will make more abatement options economically viable.

The initial share of domestically supplied factors of production is estimated based on the relative maturity of the natural gas industry and the technology intensity in each country. Table C-3 indicates the domestic input shares for the Russian Federation in 2000 and 2020.

Table C-3: Share of Domestic Inputs for the Russian Federation Natural Gas Abatement Options

Input	2000	2020
Domestic share of labor	100%	100%
Domestic share of capital	50%	83%
Domestic share of materials	75%	92%

Note: Factors are based on publicly available industry information.

C.2 Technology Change Results

This section discusses the results from the MAC analysis conducted for the major emitting countries, which are the United States, the Russian Federation, Ukraine, China, and Venezuela.

C.2.1 Technology Change Data Tables and Graphs

Based on the trends described above, shifts in the MACs for the United States, the Russian Federation, China, Ukraine, and Venezuela were developed for 10-year intervals from 2000 to 2030. Two of the MACs are discussed below to highlight the factors underlying the shifts in the curves over time. Figures C-1 and C-2 present the 2000, 2010, 2020, and 2030 MACs for the U.S. and the Russian Federation natural gas sectors. The magnitude of the shifts reflect both changes in costs and the benefits of abatement technologies and growth in production and consumption. For example, the MACs for the United States shift out steadily, reflecting the growth in gas production and consumption. In addition, technology improvements continually drive the curves downward, increasing the level of abatement for any given breakeven price.

[2] The relative leakiness factor estimates were developed using the IPCC 1996 reported regional emissions divided by the emissions factor reported for the United States and Canada. More recent studies refuted the IPCC estimate, suggesting that the Russian Federation natural gas systems are more similar to the U.S natural gas system in terms of leaks (see Lelieveld et al., 2005). However, in our technology change analysis, we use the 1996 values reported by the IPCC.

Figure C-1: Shift in the U.S. MAC for the Natural Gas Sector over 30 Years

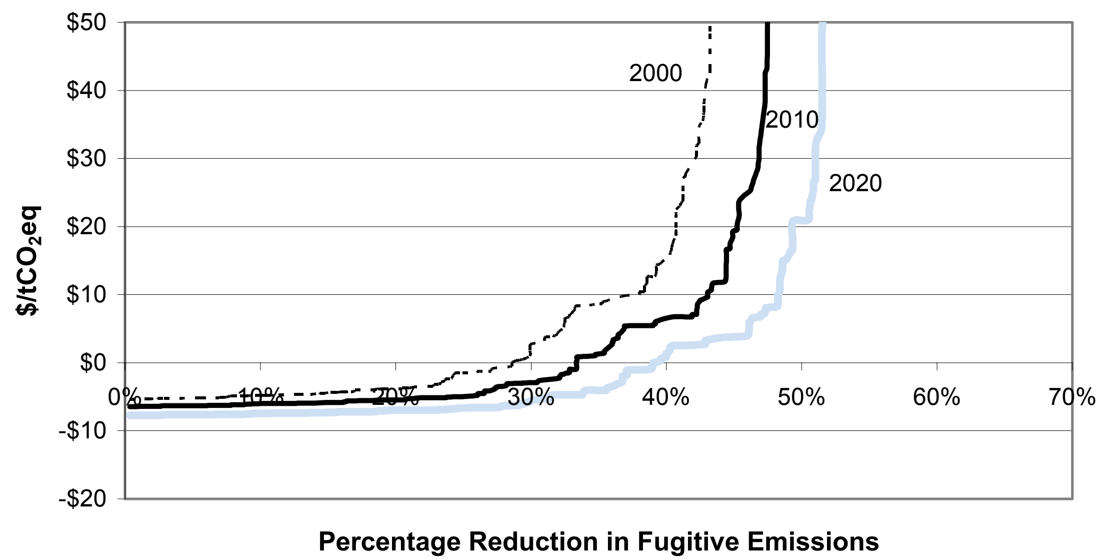
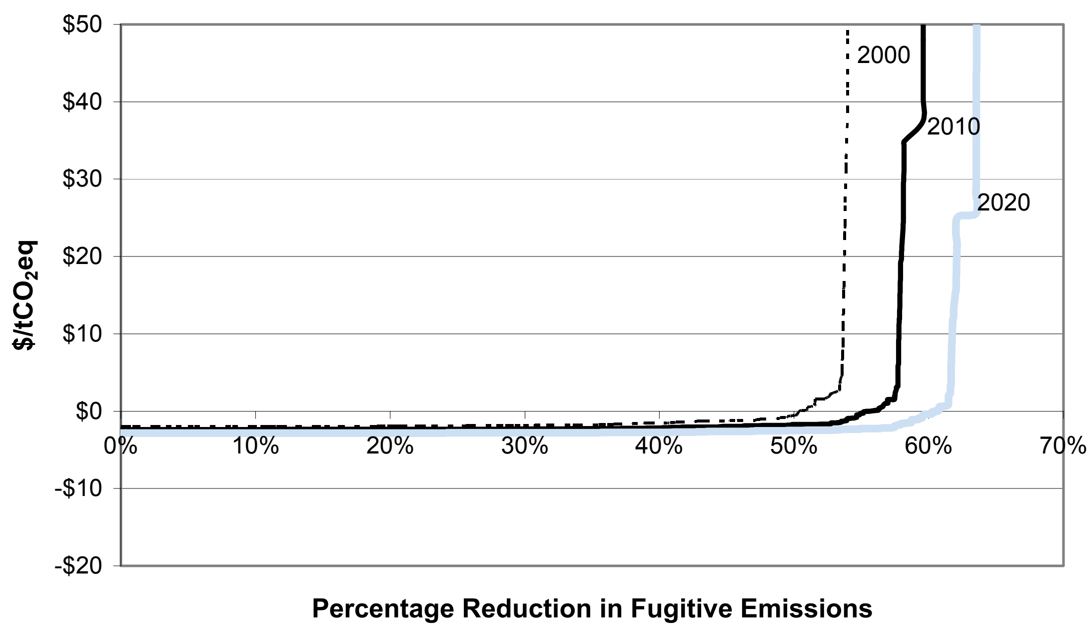


Figure C-2: Shift in The Russian Federation's MAC for the Natural Gas Sector over 30 Years



The MACs for the Russian Federation also shift out steadily as production and consumption increase. However, decreasing emissions factors, which stem from the retirement of aging components of the infrastructure, offset technology advances. As a result, MACs for the Russian Federation show little downward shift over time.

Individual country CH_4 MACs for 2010 and 2020 are provided in Table C-4. The percentages indicate the share of abatement for a given breakeven price per tCO_2eq of CH_4. Abatement for breakeven prices less than or equal to zero are referred to as "no-regret" options. For all countries, the share of no-regret options grows over time after a technology change is introduced.

Table C-4: Natural Gas MACs for Countries Included in the Technology Change Analysis

		Percentage Reduction from Baseline at Breakeven Prices ($/$tCO_2eq$)				
Year	**Country**	**$0**	**$15**	**$30**	**$45**	**$60**
2000						
	China	37.95%	43.79%	44.21%	44.41%	44.52%
	Russian Federation	50.38%	53.67%	53.83%	53.99%	55.40%
	Ukraine	44.68%	45.04%	45.16%	45.18%	47.29%
	United States	28.60%	39.78%	42.14%	43.24%	43.42%
	Venezuela	37.99%	43.73%	44.13%	44.41%	44.44%
2010						
	China	45.55%	48.64%	49.05%	49.26%	49.27%
	Russian Federation	55.48%	57.87%	58.14%	59.59%	59.61%
	Ukraine	49.38%	49.62%	51.02%	51.83%	51.85%
	United States	33.35%	44.44%	46.84%	47.45%	47.66%
	Venezuela	45.11%	48.62%	49.01%	49.13%	49.25%
2020						
	China	51.77%	53.57%	53.72%	53.79%	53.79%
	Russian Federation	60.45%	61.97%	63.53%	63.55%	63.57%
	Ukraine	53.66%	53.87%	56.03%	56.05%	57.28%
	United States	39.01%	48.60%	51.02%	51.48%	51.86%
	Venezuela	50.69%	53.15%	53.55%	53.72%	53.76%

Table C-5 summarizes the factors driving the shifts in the MACs for the natural gas sectors in terms of percentage changes from 2000 to 2020. As shown in Table C-6, the cost of abatement options decreases over time, while reduction efficiency increases. These factors combine to increase the economic viability of the mitigation options, hence lowering their breakeven price and shifting the MACs downward. The change in reduction efficiency is technology specific and thus constant across countries, increasing approximately 9.6 percent by 2020. However, changes in costs vary greatly across each country, because of the changing shares of domestic versus foreign inputs over time.

One-time costs and annual costs in the United States decrease by 27 percent and 30 percent, respectively, as a result of applying price and productivity trends. The rate of change is modest because most natural gas abatement options are relatively labor intensive, and the real wage rate is projected to increase, thereby offsetting increases in labor productivity.

Table C-5: Percentage Change by 2020 in Factors Driving the Shifts in the Natural Gas MACs

Country	Change in One-Time Costs	Change in Annual Costs	Change in Reduction Efficiency
United States	–27%	–30%	9.60%
China	–67%	–69%	9.60%
Russian Federation	–68%	–63%	9.60%
Ukraine	–71%	–63%	9.60%
Venezuela	–54%	–57%	9.60%

Table C-6: Trends Affecting MACs over Time for Natural Gas

	2020		
Trend	Lower Bound	Original Projection	Upper Bound
Scenario 1: Venezuela			
Reduction efficiency (growth rate)	4.95%	9.9%	19.80%
Scenario 2: China			
Domestic share of labor	75.00%	100.0%	100.00%
Domestic share of capital	40.00%	80.0%	100.00%
Domestic share of materials	50.00%	88.0%	100.00%
Scenario 3: Russian Federation			
Relative emissions factor: production	1.40%	2.7%	5.47%
Relative emissions factor: processing, transport and distribution	1.50%	3.0%	5.99%

Note: Scenario 3: Table values represent adjustments made to the relative emissions factor estimate based on IPCC 1996 reported emissions factors (See Section C.1. Adjustment Factors Used in Natural Gas System Technology Analysis for discussion of relative emissions factor calculations.)

China, the Russian Federation, Ukraine, and Venezuela have greater decreases in costs, because these countries are projected to increase the use of significantly lower-cost domestic capital, labor, and materials over time. The changes in costs are also a function of each country's relative price. For example, the percentage change in annual costs is not as great in the Russian Federation as in China, because China has lower domestic wages than these other countries.

C.2.2 Sensitivity Analyses

The MACs presented in Figures C-1 and C-2 are the result of simultaneously applying several technology feasibility, efficiency, and import trends. Each trend contributes to lowering the cost and/or increasing the benefits associated with abatement technologies, hence shifting the MACs. A sensitivity analysis was conducted to investigate which trends have the most significant impact on the MACs over time. Three scenarios are modeled for the development of MACs for natural gas. The first trend focuses on the rate of change in the reduction efficiency of abatement technologies. The second focuses on the share of domestic versus foreign labor, capital, and materials used in the mitigation options. The third investigates the impact of changing the emissions factors of natural gas systems over time. Table C-6 presents the lower and upper bounds used in the sensitivity analysis for the three scenarios.

The sensitivity analysis for Scenario 1 (reduction efficiency) in the year 2030 is presented in Figure C-3. The lower and upper bounds are shown as a range for the shifts of the MAC. Similarly, Figure C-4 presents the lower and upper bounds of the sensitivity analysis for Scenario 2 (the share of domestic inputs). The first two sensitivity scenarios indicate that the MACs are more sensitive to the projected trends in the share of domestic inputs and less sensitive to projected changes in reduction efficiency. This dynamic is due to the abundant availability of low-wage labor in China and the relative maturity of abatement technologies for natural gas.

Figure C-3: Sensitivity Analysis for Venezuela, 2030: Scenario 1—Reduction Efficiency

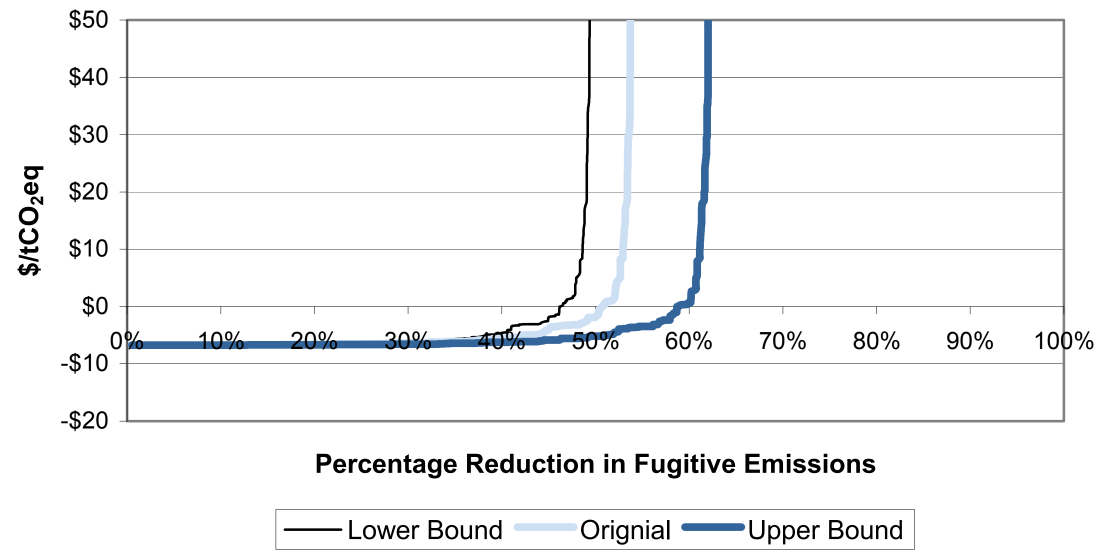
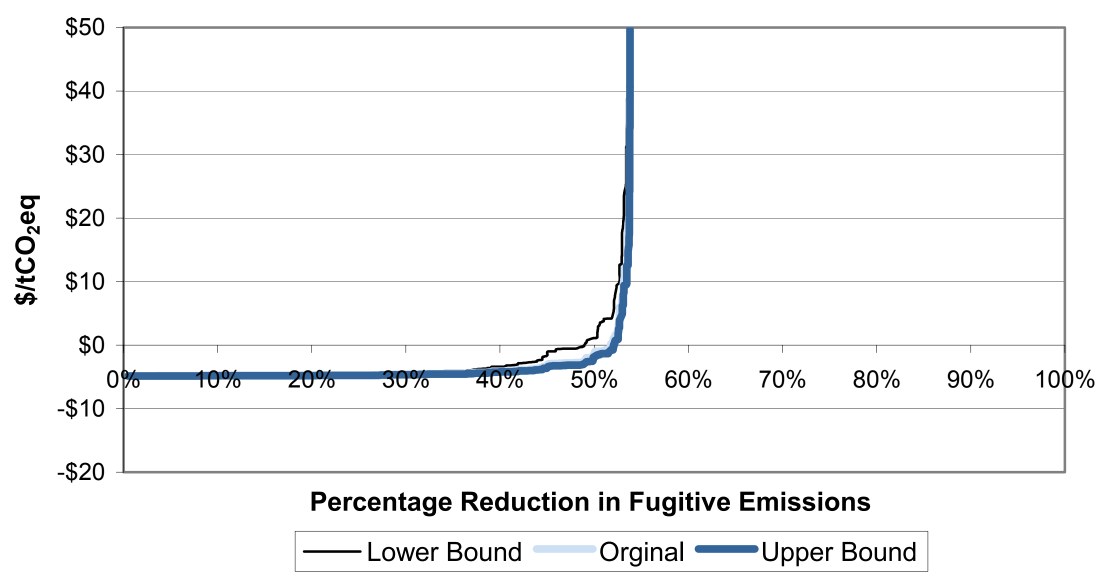
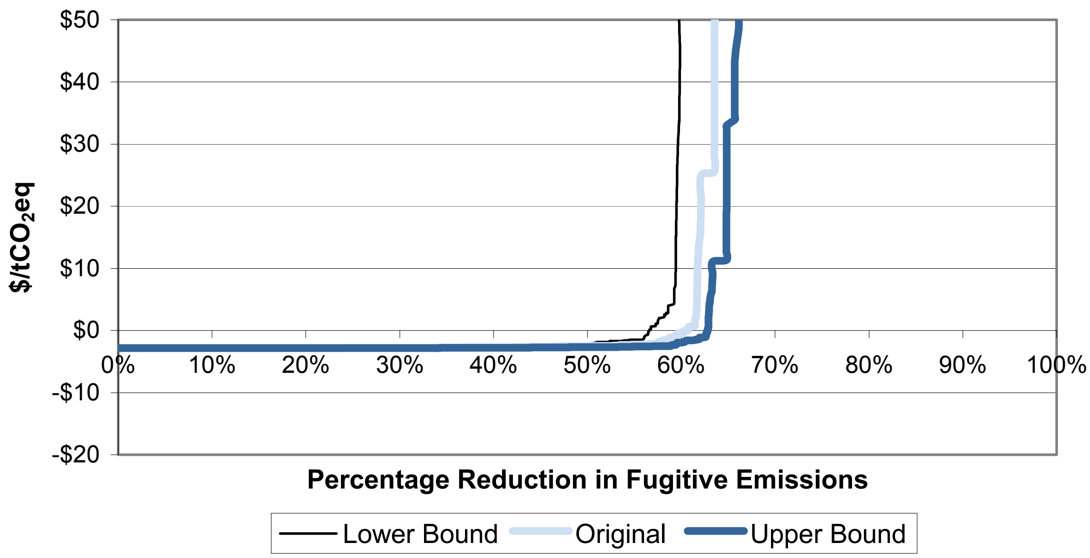


Figure C-4: Sensitivity Analysis for China, 2030: Scenario 2—Domestic Share



The third sensitivity scenario investigates the impact of applying the leakiness factors (Figure C-5). As described above, the Russian Federation natural gas infrastructure is assumed to have emissions factors that, on average, are approximately six times that of the United States in 2000. It is assumed that this factor will decrease over time as the Russian Federation replaces and upgrades its infrastructure. However, as shown in Figure C-5, the Russian Federation's MAC in 2030 is fairly sensitive to the application of this factor.

Figure C-5: Sensitivity Analysis for the Russian Federation, 2030: Scenario 3—Impact of the Average Emissions Factor



C.2.3 Activity Factors and Emissions Factors

Table C-7 illustrates the size of the U.S. natural gas system by segment and then by component base in 1992 estimates, which were published in the USEPA GRI 1996 report and are the basis for all other years' estimates (USEPA, 1996). The analysis classified the natural gas industry into four segments: production, gas processing, transmission, and distribution. Within each segment, emissions are classified as fugitive (leaks) and vented or combusted. Each type of equipment or process listed represents an emissions source from the segment of the natural gas system. The emissions, expressed in tons of CH_4, are the product of the activity factor and the annualized emissions factor, which is expressed in cubic feet of CH_4 (standard cubic feet per day [scfd]; thousand standard cubic feet of CH_4 per year [Mscfy]).

C.3 Summary and Analysis

The methods and data discussed in this section describe the successful integration of technical change with equipment-level data to estimate MACs for 2010 and 2020. MACs are generated for natural gas sectors for the United States, the Russian Federation, Ukraine, Venezuela, and China. These estimates represent improvements over previously published MACs because the equipment-level data smooth out the stepwise function (based on representative entities), and the curves are shifted over time to account for technical change.

Table C-7: Activity Factors and Emissions Factors, 1992

Segment / *Emissions Type* / Source	Emissions (Tons of CH_4)	Emissions Factor	Units	Activity Factor	Units
Production	**1,478,134.00**				
Normal Fugitives					
Gas wells (Eastern onshore)					
Appalachia (all unassociated)	6,157.85	7.11	scfd/well	123,585	wells
North Central					
Associated gas wells	—	—	scfd/well	3,507	wells
Unassociated gas wells	247.99	7.11	scfd/well	4,977	wells
Field separation equipment (Eastern onshore)					
Heaters	262.70	14.21	scfd/heater	2,638	heaters
Separators					
Appalachia	116.92	0.90	scfd/sep	18,538	separators
North Central	18.11	0.90	scfd/sep	2,871	separators
Gathering compressors					
Small reciprocating compressor					
Appalachia	419.18	12.10	scfd/comp	4,943	compressors
North Central					
Associated gas	22.93	12.10	scfd/comp	270	compressors
Unassociated gas	27.48	12.10	scfd/comp	324	compressors
Meters/piping	738.30	9.01	scfd/meter	11,693	meters
Dehydrators	102.73	21.75	scfd/dehy	674	dehydrators
Gas wells (rest of US onshore)	36,419.53	36.40	scfd/well	142,771	wells
Assoc gas well (rest of US)	—	—	scfd/well	256,226	wells
Gulf of Mexico (offshore platforms)	27,568.77	2,914.00	scfd/plat	1,350	platforms
Rest of US (offshore platforms)	181.62	1,178.00	scfd/plat	22	platforms
Field separation equipment (rest of US onshore)					
Heaters	12,701.00	57.70	scfd/heater	31,410	heaters
Separators	86,026.83	122.00	scfd/sep	100,619	separators
Gathering compressors					
Small reciprocating compressor	31,745.18	267.80	scfd/comp	16,915	compressors
Large reciprocating compressor	8,524.53	15,205.00	scfd/comp	80	compressors
Large reciprocating stations	577.95	8,247.00	scfd/station	10	stations
Meters/piping	65,780.56	52.90	scfd/meter	177,438	meters
Dehydrators	15,506.55	91.10	scfd/dehy	24,289	dehydrators
Pipeline leaks	111,334.30	53.20	scfd/mile	298,623	miles

(continued)

Table C-7: Activity Factors and Emissions Factors, 1992 (continued)

Segment / *Emissions Type* / Source	**Emissions (Tons of CH_4)**	**Emissions Factor**	**Units**	**Activity Factor**	**Units**
Vented and Combusted					
Drilling and well completion					
Completion flaring	5.63	733.00	scf/comp	400	compl/yr
Normal operations					
Pneumatic device vents	602,291.32	345.00	scfd/device	249,111	controllers
Chemical injection pumps	39,052.54	248.05	scfd/pump	22,465	active pumps
Kimray pumps	140,566.12	992.00	scf/MMscf	7,380,194	MMscf/yr
Dehydrator vents	43,386.88	275.57	scf/MMscf	8,200,215	MMscf/yr
Compressor exhaust vented					
Gas engines	126,535.33	0.24	scf/HPhr	27,460	MMHPhr
Routine maintenance					
Well workovers					
Gas wells	556.12	2,454.00	scfy/w.o.	11,803	w.o./yr
Well cleanups (LP gas wells)	105,878.08	49,570.00	scfy/LP well	111,246	LP gas wells
Blowdowns (BDs)					
Vessel BD	271.12	78.00	scfy/vessel	181,037	vessels
Pipeline BD	1,771.67	309.00	scfy/mile	298,623	miles (gath)
Compressor BD	1,626.96	3,774.00	scfy/comp	22,453	compressors
Compressor starts	3,639.75	8,443.00	scfy/comp	22,453	compressors
Upsets					
Pressure relief valves	345.62	34.00	scfy/PRV	529,440	PRV
ESD	6,767.05	256,888.00	scfy/plat	1,372	platforms
Mishaps	958.94	669.00	scfy/mile	74,656	miles
Gas Processing Plants	**697,555.00**				
Normal Fugitives					
Plants	40,224.08	7,906.00	scfd/plant	726	plants
Reciprocating compressors	321,066.39	11,196.00	scfd/comp	4,092	compressors
Centrifugal compressors	108,014.07	21,230.00	scfd/comp	726	compressors
Vented and Combusted					
Normal operations					
Compressor exhaust					
Gas engines	126,535.45	0.24	scf/HPhr	27,460	MMHPhr
Gas turbines	3,601.67	0.01	scf/HPhr	32,910	MMHPhr
AGR vents	15,814.96	6,083.00	scfd/AGR	371	AGR units
Kimray pumps	3,269.22	177.75	scf/MMscf	957,930	MMscf/yr
Dehydrator vents	20,140.36	121.55	scf/MMscf	8,630,003	MMscf/yr
Pneumatic devices	2,296.07	164,721.00	scfy/plant	726	gas plants

(continued)

Table C-7: Activity Factors and Emissions Factors, 1992 (continued)

Segment / *Emissions Type* / Source	**Emissions (Tons of CH_4)**	**Emissions Factor**	**Units**	**Activity Factor**	**Units**
Routine Maintenance					
Blowdowns/venting	56,592.96	4,060.00	Mscfy/plant	726	gas plants
Transmission and Storage	**2,252,160.00**				
Fugitives					
Pipeline leaks	3,072.41	1.54	scfd/mile	284,500	miles
Compressor stations (transmission)					
Station	104,174.80	8,778.00	scfd/station	1,693	stations
Reciprocating compressor	746,216.15	15,205.00	scfd/comp	7,003	compressors
Centrifugal compressor	148,876.59	30,305.00	scfd/comp	701	compressors
Compressor stations (storage)					
Station	58,178.33	21,507.00	scfd/station	386	stations
Reciprocating compressor	167,958.35	21,116.00	scfd/comp	1,135	compressors
Centrifugal compressor	23,782.37	30,573.00	scfd/comp	111	compressors
Wells (storage)	14,442.69	114.50	scfd/well	17,999	wells
Meter & regulator (M&R) (trans. co. interconnect)	70,694.51	3,984.00	scfd/station	2,532	stations
M&R (farm taps + direct sales)	15,675.86	31.20	scfd/station	71,694	stations
Vented and Combusted					
Normal operation					
Dehydrator vents (transmission)	1,942.42	93.72	scf/MMscf	1,079,468	MMscf/yr
Dehydrator vents (storage)	4,499.71	117.18	scf/MMscf	2,000,001	MMscf/yr
Compressor exhaust					
Engines (transmission)	186,071.04	0.24	scf/HPhr	40,380	MMHPhr
Turbines (transmission)	1,054.45	0.01	scf/HPhr	9,635	MMHPhr
Engines (storage)	22,680.58	0.24	scf/HPhr	4,922	MMHPhr
Turbines (storage)	189.22	0.01	scf/HPhr	1,729	MMHPhr
Generators (engines)	9,105.42	0.24	scf/HPhr	1,976	MMHPhr
Generators (turbines)	2.55	0.01	scf/HPhr	23	MMHPhr
Pneumatic devices transmission + storage					
Pneumatic devices transmission	211,212.47	162,197.00	scfy/device	67,823	devices
Pneumatic devices storage	48,145.26	162,197.00	scfy/device	15,460	devices
Routine maintenance/upsets					
Pipeline venting	172,884.96	31.65	Mscfy/mile	284,500	miles
Station venting trans + storage					

(continued)

Table C-7: Activity Factors and Emissions Factors, 1992 (continued)

Segment / *Emissions Type* / Source	**Emissions (Tons of CH_4)**	**Emissions Factor**	**Units**	**Activity Factor**	**Units**
Station venting transmission	141,729.77	4,359.00	Mscfy/station	1,693	cmp stations
Station venting storage	32,305.42	4,359.00	Mscfy/station	386	cmp stations
LNG Storage					
LNG stations	9,646.15	21,507.00	scfd/station	64	stations
LNG reciprocating compressors	36,403.31	21,116.00	scfd/comp	246	compressors
LNG centrifugal compressors	12,426.82	30,573.00	scfd/comp	58	compressors
LNG compressor exhaust					
LNG engines	3,414.53	0.24	scf/HPhr	741	MMHPhr
LNG turbines	17.73	0.01	scf/HPhr	162	MMHPhr
LNG station venting	5,356.34	4,359.00	Mscfy/station	64	cmp stations
Distribution	**1,495,565.00**				
Normal Fugitives					
Pipeline leaks					
Mains—cast iron	253,387.12	238.70	Mscf/mile-yr	55,288	miles
Mains—unprotected steel	173,706.87	110.19	Mscf/mile-yr	82,109	miles
Mains—protected steel	26,623.73	3.12	Mscf/mile-yr	444,768	miles
Mains—plastic	94,324.89	19.30	Mscf/mile-yr	254,595	miles
Total pipeline miles				836,760	.
Services—unprotected steel	177,815.33	1.70	Mscf/service	5,446,393	services
Services—protected steel	69,000.53	0.18	Mscf/service	20,352,983	services
Services—plastic	3,161.82	0.01	Mscf/service	17,681,238	services
Services—copper	1,138.36	0.25	Mscf/service	233,246	services
Total services				43,713,860	
Meter/regulator (M&R) (city gates)					
M&R > 300	108,277.61	179.80	scfh/station	3,580	stations
M&R 100–300	221,882.88	95.60	scfh/station	13,799	stations
M&R < 100	5,346.34	4.31	scfh/station	7,375	stations
Regulator > 300	112,573.59	161.90	scfh/station	4,134	stations
R-Vault > 300	530.82	1.30	scfh/station	2,428	stations
Regulator 100–300	86,512.45	40.50	scfh/station	12,700	stations
R-Vault 100–300	172.75	0.18	scfh/station	5,706	stations
Regulator 40–100	6,575.79	1.04	scfh/station	37,593	stations
R-Vault 40–100	485.01	0.09	scfh/station	33,337	stations
Regulator < 40	355.96	0.13	scfh/station	15,913	stations

(continued)

Table C-7: Activity Factors and Emissions Factors, 1992 (continued)

Segment / *Emissions Type* / Source	Emissions (Tons of CH_4)	Emissions Factor	Units	Activity Factor	Units
Customer					
Residential	106,499.11	138.50	scfy/meter	40,049,306	outdr meters
Commercial/industry	4,237.87	47.90	scfy/meter	4,607,983	meters
Vented					
Routine maintenance					
Pressure relief valve releases	803.29	0.05	Mscf/mile	836,760	mile main
Pipeline blowdown	2,541.16	0.10	Mscfy/mile	1,297,569	miles
Upsets					
Mishaps (dig-ins)	39,612.18	1.59	mscfy/mile	1,297,569	miles
Total Emissions	**5,923,415.00**				

AGR = Acid gas removal; BD = blowdown; ESD = Emergency shutdown system; LNG = Liquid natural gas; LP = Liquid propane; R-vault = Regulator vault.

The inclusion of technical change in MACs over time is important because it provides researchers and policy makers more accurate behavioral responses to potential future carbon prices. Projected changes over time in technical applicability and reduction efficiency, and in the share of domestic versus foreign inputs, lower the cost and increase the benefits of abatement technologies. This, in turn, shifts MACs downward, potentially increasing the adoption at any given carbon price.

Table C-8 contains a brief description of the major categories of natural gas abatement options.

Table C-8: Description of Natural Gas Abatement Options

Abatement Option	Description
Installing plunger lift systems in gas wells (production sector)	Installing plunger lift systems is an alternative to beam pumps and blowing down the well for removing fluids in mature wells.
Convert gas pneumatic controls to instrument air (production, processing, transmission, and distribution sectors)	Substitute compressed air for pressurized natural gas; instrument air systems eliminate the constant bleed of natural gas from controllers—one of the largest sources of CH_4 emissions in the natural gas industry.
Optimize glycol circulation and install flash tank separators in dehydrators (production and processing sectors)	This reduces the glycol circulation rate in dehydrators.
Options for reducing CH_4 emissions from pneumatic devices in the natural gas industry (production, processing, transmission, and distribution sectors)	Replace with low-bleed devices, retrofitting, and improving the maintenance of high-bleed pneumatic devices. Natural gas emissions from pneumatic control devices are one of the largest sources of CH_4 emissions in the natural gas industry.
Reducing emissions when taking compressors offline (production, processing, transmission, and distribution sectors)	Change operational practices when compressors are taken offline.

(continued)

Table C-8: Description of Natural Gas Abatement Options (continued)

Abatement Option	Description
Reducing CH_4 emissions from compressor rod packing systems (production, processing, transmission, and distribution sectors)	Applies an economic replacement threshold approach to replacing worn compressor rod packing rings and rods. Gas leaks from compressor rods represent one of the largest sources of emissions at natural gas compressor stations.
Replacing gas-assisted glycol pumps with electric pumps (production and processing sectors)	Replace gas-assisted glycol pumps on glycol dehydrators with electric pumps.
Replacing wet seals with dry seals in centrifugal compressors (production, transmission, and distribution sectors)	Dry seals use high-pressure gas to seal a compressor and emit less CH_4.
Directed inspection and maintenance at gas processing plants and booster stations (processing sector)	Implementing a DI&M program eliminates as much as 96 percent of gas losses and a corresponding 80 percent of fugitive CH_4 emissions from equipment leaks. These leaks account for more than 80 percent of natural gas losses from gas processing plants and booster stations.
Using hot taps for in-service pipeline connections (transmission and distribution sectors)	Hot taps make new pipeline connections while keeping transmission and distribution pipelines in service. Using hot taps also reduces CH_4 emissions by avoiding the venting of pipeline contents to the atmosphere.
Using pipeline pumpdown techniques to lower gas line pressure before maintenance (transmission and distribution sectors)	Using fixed and portable compressors to lower pipeline pressure prior to maintenance and repair significantly reduces CH_4 emissions. Pipeline pumpdown techniques remove product from the section of pipeline under repair, thereby reducing the volume of natural gas vented to the atmosphere.
Directed inspection and maintenance at compressor stations (transmission and distribution sectors)	Implementing a DI&M program at compressor stations is a proven, cost-effective way to detect, measure, prioritize, and repair leaks to reduce CH_4 emissions. Fugitive emissions from equipment leaks at compressor stations represent one of the largest sources of CH_4 emissions in the natural gas transmission industry.
Directed inspection and maintenance at gate stations and surface facilities (transmission and distribution sectors)	Implementing a DI&M program at gate stations and surface facilities is a method for companies in the distribution sector to detect, measure, prioritize, and repair leaks to reduce CH_4 emissions.
Composite wrap for nonleaking pipeline defects (transmission and distribution sectors)	Using composite wrap to repair nonleaking pipeline defects as an alternative to pipeline replacement avoids the venting of the damaged pipe—reducing CH_4 emissions.

Source: USEPA, 2004.

C.4 References

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Appendix D: Supporting Materials for Analysis of Oil Systems

D.1 Oil Sector Emissions Tables

Table D-1. 2002 CH_4 Emissions from Oil Production Field Operations

Activity/Equipment	Emissions Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					**53.047**
Oil tanks	18.00	scf of CH_4/bbl crude	1,491	MMbbl/yr (nonstripper wells)	26.684
Pneumatic devices high-bleed	330.00	scfd CH_4/device	141,771	No. of high-bleed devices	17.097
Pneumatic devices low-bleed	52.00	scfd CH_4/device	263,299	No. of low-bleed devices	4.997
Chemical injection pumps	248.00	scfd CH_4/pump	28,380	No. of pumps	2.570
Vessel blowdowns	78.00	scfy CH_4/vessel	185,106	No. of vessels	0.014
Compressor blowdowns	3,775.00	scf/yr of CH_4/compressor	2,512	No. of compressors	0.009
Compressor starts	8,443.00	scf/yr. of CH_4/compressor	2,512	No. of compressors	0.021
Stripper wells	2,345.00	scf/yr of CH_4/stripper well	322,767	No. of stripper wells vented	0.818
Well completion venting	733.00	scf/completion	4,964	Oil well completions	0.004
Well workovers	96.00	scf CH_4/workover	39,750	Oil well workovers	0.004
Pipeline pigging	2.40	scfd of CH_4/pig station	0	No. of crude pig stations	0.000
Offshore platforms Gulf of Mexico	1,283.00	scfd CH_4/platform	1,876	No. of oil platforms	0.878
Offshore platforms other U.S. areas	1,283.00	scfd CH_4/platform	23	No. of oil platforms	0.011
Fugitive Emissions					**2.592**
Offshore platforms Gulf of Mexico	56.00	scfd CH_4/platform	1,876	No. of oil platforms	0.038
Offshore platforms other U.S. areas	56.00	scfd CH_4/platform	23	No. of oil platforms	0.000
Oil wellheads (heavy crude)	0.13	scfd/well	14,610	No. of hvy. crude wells	0.001
Oil wellheads (light crude)	16.60	scfd/well	192,623	No. of lt. crude wells	1.169
Separators (heavy crude)	0.15	scfd CH_4/separator	10,888	No. of hvy. crude seps.	0.001
Separators (light crude)	14.00	scfd CH_4/separator	99,099	No. of lt. crude seps.	0.501
Heater/treaters (light crude)	19.00	scfd CH_4/heater	75,128	No. of heater treaters	0.526
Headers (heavy crude)	0.08	scfd CH_4/header	13,825	No. of hvy. crude hdrs.	0.000
Headers (light crude)	11.00	scfd CH_4/header	42,859	No. of lt. crude hdrs.	0.170
Floating roof tanks	338,306.00	scf CH_4/floating roof tank/yr.	24	No. of floating roof tanks	0.008
Compressors	100.00	scfd CH_4/compressor	2,512	No. of compressors	0.092

(continued)

Table D-1. 2002 CH_4 Emissions from Oil Production Field Operations (continued)

Activity/Equipment	Emissions Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Fugitive Emissions					**2.592**
Large compressors	16,360.00	scfd CH_4/compressor	0	No. of large comprs.	0.000
Sales areas	41.00	scf CH_4/loading	1,747,462	Loadings/year	0.071
Pipelines	0.00	scfd of CH_4/mile of pipeline	19,149	Miles of gathering line	0.000
Well drilling	0.00	scfd of CH_4/oil well drilled	8,825	No. of oil wells drilled	0.000
Battery pumps	0.24	scfd of CH_4/pump	159,000	No. of battery pumps	0.014
Combustion Emissions					**4.159**
Gas engines	0.24	scf CH_4/HP-hr	158,260	MMHP-hr	3.798
Heaters	0.52	scf CH_4/bbl	2,097.30	MBbl/yr	0.001
Well drilling	2,453.00	scf CH_4/well drilled	5,825	Oil wells drilled 1995	0.014
Flares	20.00	scf CH_4/Mcf flared	587,049,582	Mcf flared/yr	0.012
Offshore platforms Gulf of Mexico	481.00	scfd CH_4/platform	1,876	No. of oil platforms	0.329
Offshore platforms other U.S. areas	481.00	scfd CH_4/platform	23	No. of oil platforms	0.004
Process Upset Emissions					**0.554**
Platform emergency shutdowns	256,888.00	scfy/platform	1,899	No. of platforms	0.488
Pressure relief valves	35.00	scf/yr/PR valve	175,187	No. of PR valves	0.006
Well blowouts offshore	5.00	MMscf/blowout	2.25	No. of blowouts/yr	0.011
Well blowouts onshore	2.50	MMscf/blowout	19.40	No. of blowouts/yr	0.049
Total					**60.350**

Source: USEPA, 2004. Table 3-41: 2002 CH_4 Emissions from Petroleum Production Field Operations.

Note: These estimates do not include emissions reductions reported by the Natural Gas STAR Program.

Table D-2. 2002 CH_4 Emissions from Oil Transportation

Activity/Equipment	Emissions Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					0.221
Tanks	0.021	scf CH_4/yr/bbl of crude delivered to refineries	5,456.0	MMbbl crude feed/yr	0.112
Truck loading	0.520	scf CH_4/yr/bbl of crude transported by truck	51.1	MMbbl crude feed/yr	0.027
Marine loading	2.544	scf CH_4/1,000 gal. crude marine loadings	24,149,670.0	1,000 gal./yr loaded	0.061
Rail loading	0.520	scf CH_4/yr/bbl of crude transported by rail	7.5	MMbbl. crude by rail/yr	0.004
Pump station maintenance	36.800	scf CH_4/station/yr	575.0	No. of pump stations	0.000
Pipeline pigging	39.000	scfd of CH_4/pig station	1,150.0	No. of pig stations	0.016
Fugitive Emissions					**0.050**
Pump stations	25.000	scfCH_4/mile/yr.	57,509.0	No. of miles of crude p/l	0.001
Pipelines	0.000	scf CH_4/bbl crude transported by pipeline	7,082.0	MM bbl crude piped	0.000
Floating roof tanks	58,965.000	scf CH_4/floating roof tank/yr.	824.0	No. of floating roof tanks	0.049
Combustion Emissions					**0.000**
Pump Engine Drivers	0.240	scf CH_4/hp-hr	NA	No. of hp-hrs	NA
Heaters	0.521	scf CH_4/bbl.burned	NA	No. of bbl. burned	NA
Total					0.271

Source: USEPA, 2004. Table 3-42: 2002 CH_4 Emissions from Petroleum Transportation.

NA = Data unavailable.

Table D-3. 2002 CH_4 Emissions from Oil Refining

Activity/Equipment	Emissions Factor	Units	Activity Factor	Units	Emissions (Bcf/yr)
Vented Emissions					**1.2200**
Tanks	20.600	scfCH_4/Mbbl	19,181	Mbbl/cd heavy crude feed	0.0140
System blowdowns	137.000	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.7460
Asphalt blowing	2555.000	scfCH_4/Mbbl	492	Mbbl/cd production	0.4590
Fugitive Emissions					**0.0870**
Fuel gas system	439.000	McfCH_4/refinery/yr	145	Refineries	0.0640
Floating roof tanks	587.000	scf CH_4/floating roof tank/yr.	767	No. of floating roof tanks	0.0000
Wastewater treating	1.880	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.0100
Cooling towers	2.360	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.0130
Combustion Emissions					**0.0910**
Atmospheric distillation	3.610	scfCH_4/Mbbl	15,180	Mbbl/cd refinery feed	0.0200
Vacuum distillation	3.610	scfCH_4/Mbbl	6,665	Mbbl/cd feed	0.0090
Thermal operations	6.020	scfCH_4/Mbbl	2,075	Mbbl/cd feed	0.0050
Catalytic cracking	5.170	scfCH_4/Mbbl	5,194	Mbbl/cd feed	0.0100
Catalytic reforming	7.220	scfCH_4/Mbbl	3,186	Mbbl/cd feed	0.0080
Catalytic hydrocracking	7.220	scfCH_4/Mbbl	1,338	Mbbl/cd feed	0.0040
Hydrorefining	2.170	scfCH_4/Mbbl	1,826	Mbbl/cd feed	0.0010
Hydrotreating	6.500	scfCH_4/Mbbl	8,376	Mbbl/cd feed	0.0200
Alkylation/polymerization	12.600	scfCH_4/Mbbl	1,119	Mbbl/cd feed	0.0050
Aromatics/isomeration	1.800	scfCH_4/Mbbl	932	Mbbl/cd feed	0.0010
Lube oil processing	0.000	scfCH_4/Mbbl	152	Mbbl/cd feed	0.0000
Engines	0.006	scfCH_4/hp-hr	1,467	MMhp-hr/yr	0.0080
Flares	0.189	scfCH_4/Mbbl	14,947	Mbbl/cd refinery feed	0.0010
Total					1.3996

Source: USEPA, 2004. Table 3-43: 2002 CH_4 Emissions from Petroleum Refining.

D.2 References

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Appendix E: MSW Landfill Sector—Incorporating Technology Change to MAC Analysis

This appendix provides an overview of recent efforts to account for limitations in the EMF-21 MAC analysis by introducing a new framework that accounts for technology changes in the CH_4 mitigation options for landfills. In the following discussion, we present the methodology for incorporating technology change and develop revised MAC curves for 2000, 2010, and 2020. We present the results of our analysis for five major emitting countries, including the United States, China, Ukraine, South Africa, and Mexico. We also include sensitivity analysis to key technology change assumptions used in the analysis.

This analysis explicitly models changes in input costs, productivity, and reduction efficiency of abatement options over time. One-time capital costs and O&M costs are broken into their factor inputs (capital, materials, labor and energy) so that individual technology trends (changes in prices and productivity) can be applied. Changes in these input factors are expressed in terms of the annual percentage change in price and productivity. Price trends reflect changes in production/input costs, and productivity trends reflect advances in technologies and processes that make constant levels of production possible with fewer inputs. The price and productivity trends over time are then used to adjust one-time capital costs and O&M costs, which in turn affects the economic viability of the option (i.e., the breakeven price). For additional details on the technical change methodology, see Gallaher and Delhotal (2005).

E.1 Adjustment Factors Used in the Landfill Sector Technology Assessment

The USEPA developed the landfill population database used for the MAC analysis, and it contains characteristics (e.g., size, waste acceptance rate) for all landfills in the United States. For the development of the U.S. MAC, the database was filtered to remove all landfills with a design capacity greater than 2.5 million megagrams (or 2.9 million short tons) in an attempt to adequately capture only landfills that are not subject to regulation in the United States. Regulated landfills are accounted for in the baseline and thus are not included in emissions projections.

Because of data limitations, the U.S. landfill inventory and cost data were also used to characterize landfills in other countries. This is reasonable because managed landfills are similar worldwide. The analysis for developing countries includes the larger landfills that were omitted in the United States' case.

E.1.1 Cost Distributions

Information on the distribution of capital, materials, labor, and energy costs was not provided by the engineering cost model. A default set of cost distribution rules was used for input factor costs. The default rules were developed using the information from the USEPA Landfill Methane Outreach Program's project database, combined with knowledge gained from interviews with landfill operations experts. Table E-1 specifies the default cost distribution rules used in the landfill MAC model.

Table E-1: Default Cost Distribution Rules for Landfills

Costs	Factors of Production (Percentage of Total Cost)			
	Capital	Labor	Materials	Energy
One-time installed capital	30%	70%	0%	0%
Annual O&M	0%	25%	25%	50%

O&M = Operation and maintenance.

E.1.2 Characterizing International Landfills

The USEPA's Landfill Inventory Database provides detailed information that characterizes the U.S. landfill population. However, there is significantly less information available for landfills in other countries such as China, South Africa, Mexico, and Ukraine. As a result, each country's landfill population distribution is identical to the United States' population and then scaled up to meet the USEPA's baseline estimates for landfills in these countries.

Although this may be the best option given the current information available, landfills in different countries have some important differences. Characteristics that vary across countries include composition, climate, waste acceptance rates, and capacity. For example, the composition of waste may vary depending on the level of recycling that occurs. The presence of paper in an average landfill is much lower in countries such as China and Mexico. These differences may reduce the CH_4 generation rate per year affecting a project's ability to recoup one-time and annual costs.

E.1.3 Accounting for Climate Variations by Country

The CH_4 generation rate constant (k) in the first order decay equations are generally 4 percent for a typical climate and 2 percent for arid climates per year. To account for differences in moisture across countries, different distributions were assigned by country, as shown in Table E-2. The distribution of landfills in the United States is 47 percent moist, 33 percent typical, and 20 percent arid, respectively. However, other countries such as China have large population centers located in more rainy climates and have a different distribution of landfills by climate.

Table E-2: Percentage Distribution of Landfills by Climate, by Country

Country	> 40 inches	20–40 inches	< 20 inches
United States	47	33	20
China	40	40	20
Ukraine	50	40	10
South Africa	40	30	30
Mexico	25	45	30

Source: Expert judgment.

E.1.4 Share of Domestically Supplied Factors of Production for Landfill Options

Currently, in developing countries a large portion of the capital and materials required to implement the abatement technology is imported. For this reason, the USEPA estimated an initial share of domestically supplied production inputs. However, it is assumed that technical information is transferred over time, ultimately resulting in a shift away from imported inputs and toward domestically supplied input.

Initial shares of domestically supplied factors of production are estimated for China, Ukraine, South Africa, and Mexico based on the presence of skilled labor and the overall maturity of the waste management practices in each country. Table E-3 identifies the domestic input shares for China in 2000 and 2020.

Table E-3: Share of Domestic Inputs for China's Landfill Sector

	2000	2020
Domestic share of labor	75%	92%
Domestic share of capital	15%	53%
Domestic share of materials	50%	75%

Source: Expert judgment.

E.2 Results

This section discusses the results from the MAC analysis of selected countries, including China, Mexico, South Africa, Ukraine, and the United States.

E.2.1 Data Tables and Graphs

Based on trends described above, the USEPA developed MACs for China, Mexico, South Africa, Ukraine, and the United States in 10-year intervals from 2000 to 2030. The results for the United States' and South Africa's MACs are discussed below to demonstrate how different factors affect the shifts in the curves over time. Figures E-1 and E-2 present 10-year interval shifts in the MACs for the United States and South Africa landfill sectors, respectively, over a period of 30 years starting in 2000. The magnitude of the shifts reflects trends in the fraction of waste disposed of at landfills over time and changes in the cost of production inputs. The steady shift downward is driven by the technology improvements, increasing the percentage reduction in baseline emissions at a given breakeven price.

South Africa's MAC similarly shifts steadily over the 30-year time period, reflecting cost reductions from technology advances and the shift toward more domestically supplied production inputs.

Individual country MACs for 2000, 2010, and 2020 are provided in Table E-4. The percentages indicate the share of baseline emissions reduced at the given breakeven prices. For five major emitting countries, analysis is conducted that explicitly accounts for technical change. Breakeven prices less than or equal to zero are referred to as "no-regret" options. For all countries, the share of no-regret options grows over time after a technology change is introduced.

South Africa and Ukraine both experience significant reductions in 2020 even at a breakeven price of –$20. This may reflect the projected trend in some countries of adopting better waste management practices, which results in a larger fraction of organic waste being disposed of in managed landfills.

E.2.2 Sensitivity Analyses

The MAC curves presented in Figures E-1 and E-2 and Table E-4 are the result of simultaneously applying several technology feasibility, efficiency, and import trends. Each contributes to lowering the cost and/or increasing the benefits associated with abatement technologies and hence shifts the MACs. Sensitivity analysis is performed to elucidate which trends have the most significant impact on the MACs over time.

Figure E-1: Shift in the U.S. MAC for Landfills over 20 Years

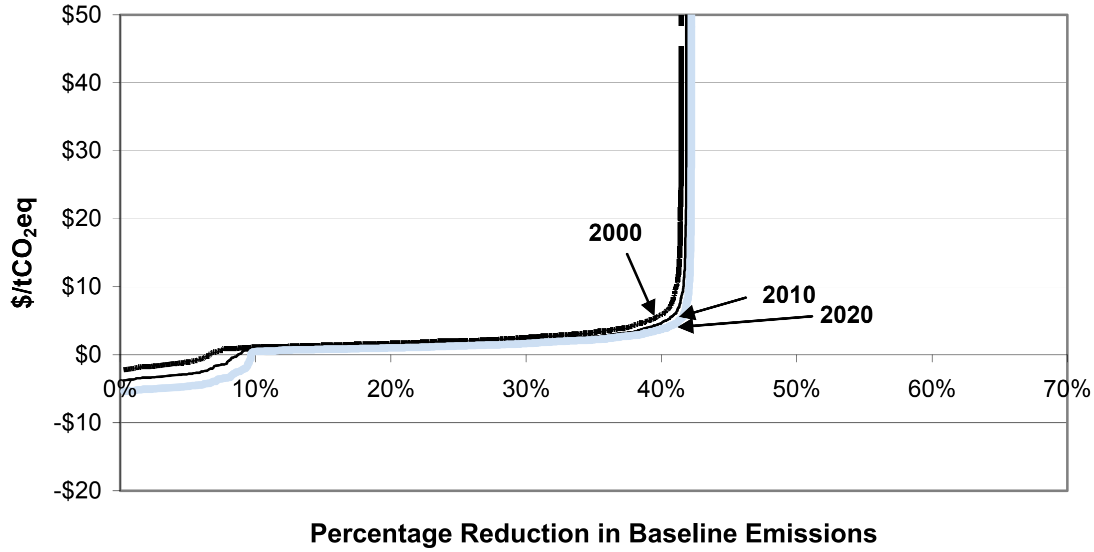


Figure E-2: Shift in South Africa's MAC for Landfills over 30 Years

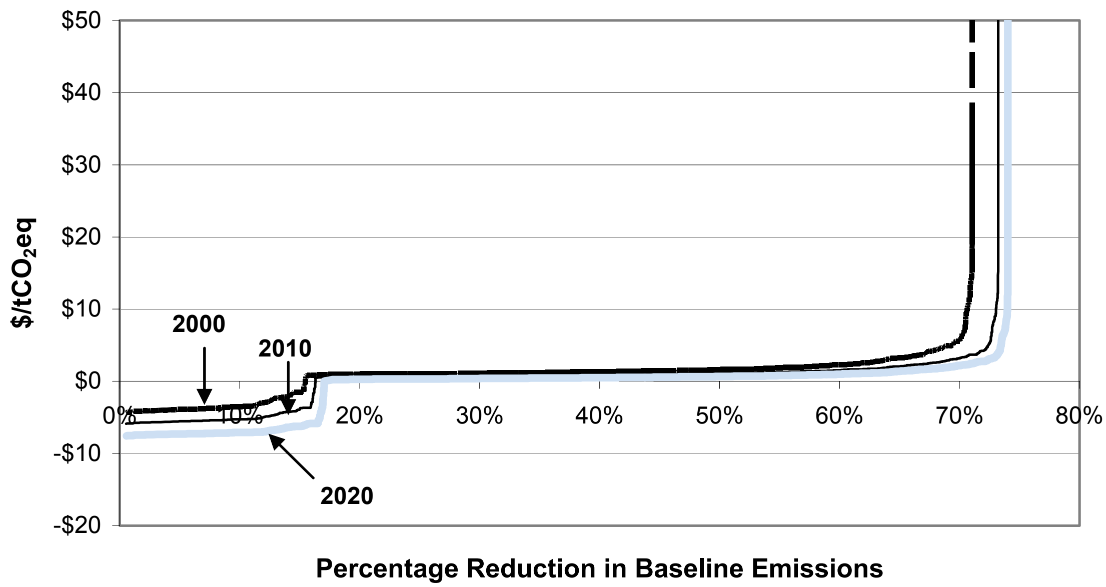


Table E-4: Landfill MACs for Countries Included in the Analysis

	2010					2020				
Country	$0	$15	$30	$45	$60	$0	$15	$30	$45	$60
China	56.34%	73.62%	73.62%	73.62%	73.62%	68.32%	74.21%	74.21%	74.21%	74.21%
Mexico	47.63%	76.93%	76.93%	76.93%	76.93%	63.22%	75.61%	75.61%	75.61%	75.61%
South Africa	16.34%	73.30%	73.32%	73.32%	73.32%	17.05%	74.10%	74.11%	74.11%	74.11%
Ukraine	69.80%	73.57%	73.57%	73.57%	73.57%	72.25%	74.17%	74.17%	74.17%	74.17%
United States	8.68%	41.81%	41.88%	41.89%	41.89%	9.68%	42.19%	42.26%	42.26%	42.27%

Two sensitivity scenarios are modeled for the development of Mexico's and Ukraine's MAC curves for landfills: the first scenario focuses on the distribution of Mexican landfills located in moist, typical, and arid climates, and the second scenario focuses on the share of domestic versus foreign labor, capital, and materials used in the mitigation options applied in Ukraine. Table E-5 presents the lower and upper bounds used in the sensitivity analysis for the two scenarios.

Table E-5: Trends Affecting MACs over Time for Landfills

		2020		
Trend	2000	Lower Bound	Original Projection	Upper Bound
Scenario 1: Mexico				
Share of landfills in tropical climates	25%	0.0%	25.0%	55.0%
Share of landfills in typical climates	45%	45.0%	45.0%	45.0%
Share of landfills in arid climates	30%	55.0%	30.0%	0.0%
Scenario 2: Ukraine				
Domestic share of labor	100%	100.0%	100.0%	100.0%
Domestic share of capital	50%	66.5%	85.0%	100.0%
Domestic share of materials	75%	82.5%	90.0%	97.5%

The results from Scenario 1 (climate distribution) in the year 2020 are presented in Figure E-3. The lower and upper bounds are shown as a change in the overall distribution of landfills located in each specified climate. Climate in this case denotes the amount of rain fall received each year, and the percentage distribution reflects the number of landfills located in each climate type. The second sensitivity analysis results are presented in Figure E-4. The two sensitivity scenarios indicate that the MAC curves are not sensitive to projected trends in the share of domestic input and are marginally sensitive to changes in the distribution of landfill by climate type because of the large difference between the costs for a direct-use system and the estimated benefits derived from the project. Overall the benefits greatly outweigh any increase in costs or change in the amount of gas produced at landfills, leaving the MACs largely unaffected as Figures E-3 and E-4 show. The driving factor in determining the breakeven price is the trend in the market price of natural gas.

Figure E-3: Sensitivity Analysis for Mexico, 2020: Scenario 1 Climate Distribution

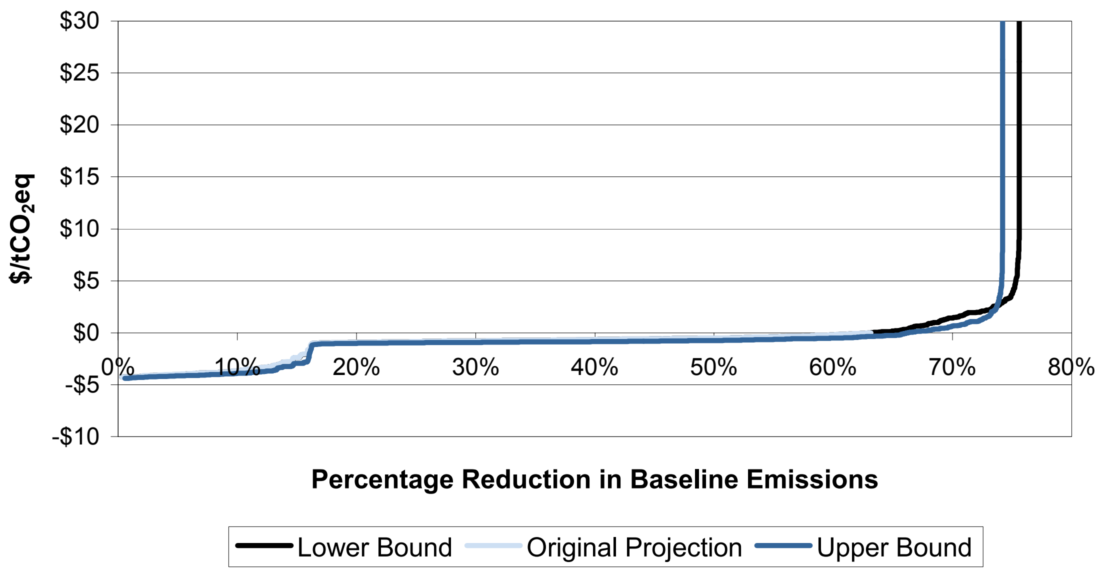
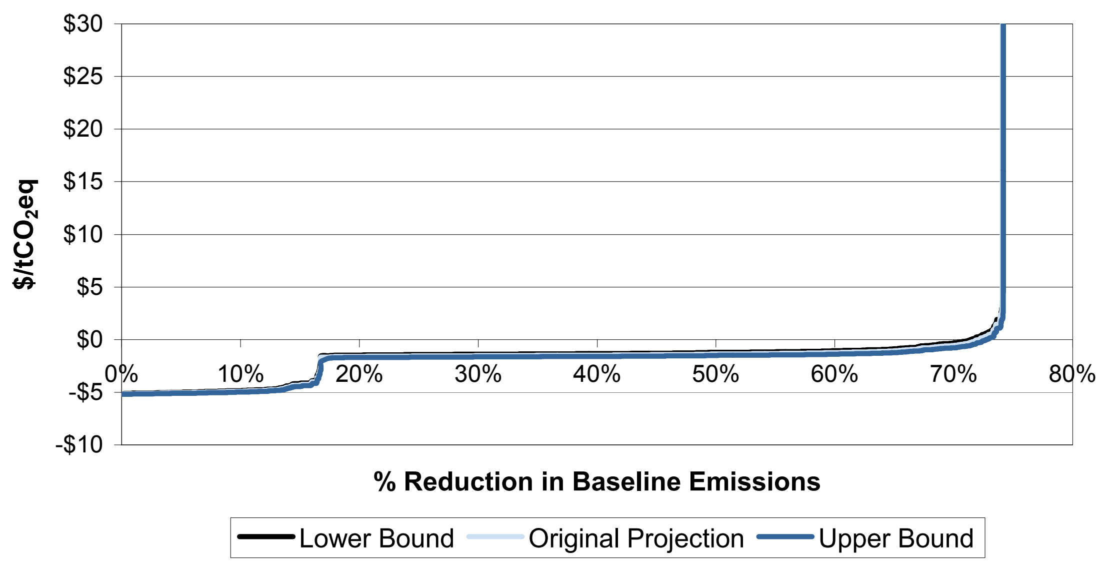


Figure E-4: Sensitivity Analysis for Ukraine, 2020: Scenario 2 Domestic Share



E.3 Summary and Analysis

The methods and data discussed in this chapter describe the successful integration of technical change with landfill population data to estimate MACs for 2010 and 2020. MACs are generated for China, Mexico, South Africa, Ukraine, and the United States. These estimates represent improvements over previously published MACs because the landfill population data smooth out the stepwise function and the curves are shifted over time to account for technical change.

E.4 References

Gallaher, M., and K.C. Delhotal. 2005. "Modeling the Impact of Technical Change on Emissions Abatement Investments in Developing Countries." *Journal of Technology Transfer* 30 1/2, 211-255.

Appendix F: Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Refrigeration and Air-Conditioning

Cost and Emissions Reduction Analysis for Leak Repair

The following describes the cost and emissions inputs used to derive the final dollars per ton of carbon dioxide equivalent (tCO_2eq) for the leak repair option, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** A one-time cost of approximately $1,480 is assumed for performing more significant, small repairs on larger systems, such as maintenance of the purge system or replacement of a gasket or O-ring. This cost is based on an estimate provided by the USEPA (1998), adjusted to 2000 dollars, which accounts for parts and labor needed to perform the repair.
- **Annual Costs.** Because the leak repair is assumed to be a one-time event, no annual costs are associated with this option.
- **Cost Savings.** An annual cost savings is associated with reduced refrigerant loss. The cost of refrigerant (assumed to be R-404A) is estimated to be $16.15/kg,[1] and approximately 163 kg of refrigerant per leak repair are estimated to be saved each year, assuming the leakage of a large supermarket system is reduced from 25 to 15 percent,[2] resulting in an annual cost savings of approximately $2,637 per leak repair.
- **Emissions Reductions.** Under the leak repair option described above, approximately 163 kilograms of R-404A refrigerant emissions can be avoided in 1 year from a large supermarket system containing 1,633 kilograms of refrigerant, assuming that system leakage is reduced from 25 to 15 percent per year. This leakage reduction results in an annual emissions reduction of approximately 532 tCO_2eq per job (i.e., 163 kilograms or 0.163 metric tons of refrigerant, multiplied by the GWP of 3,260).

Cost and Emissions Reduction Analysis for Refrigerant Recovery and Recycling

The following describes cost and emissions inputs used to derive the final dollars per tCO_2eq for the refrigerant recovery option, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** The one-time cost associated with this option is the cost of recovery or recovery and recycling equipment, which depends on the equipment type. The cost of a high-pressure recovery unit is assumed to be approximately $860, based on the average cost of four recovery scenarios: (1) recovery from MVACs at service, (2) recovery from MVACs at disposal, (3) recovery from stationary equipment at service, and (4) recovery from stationary equipment at disposal (USEPA, 1998; 2001b). This cost is annualized over the lifetime of the equipment (assumed to be five years) and expressed as a cost per job (see below).
- **Annual Costs.** All costs associated with this option, including capital costs, are expressed in terms of cost per job. The cost per job was calculated by multiplying the average additional labor required by the technician to recover the refrigerant charge (from 5 to 10 minutes, depending on recovery scenario) by the average labor rate ($50 per hour) and the average operating costs

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[1] Cost of R-404A is based on the list price quoted by Baker Distributing (2005), deflated to 2000 dollars.

[2] It is assumed that the system is used in a 60,000-square foot supermarket, and contains a refrigerant charge of 1,633 kg (ADL, 2002).

(which incorporates both the annualized costs of equipment and energy use). Based on this methodology, the average job is estimated to cost approximately $10.10 (USEPA, 1998; 2001b). This analysis assumes that all recovered refrigerant is reused; therefore, no refrigerant reclamation or destruction costs are included.

- **Cost Savings.** Because this analysis assumes that all recovered refrigerant is reused, cost savings are associated with this option. Specifically, as a result of the average cost of recovered refrigerant (R-134a, R-404A, and R-407C), calculated to be approximately $16.55 per kilogram[3] (the average for the four scenarios described above, considering the likely refrigerants involved), and an average recoverable charge of 0.83 kilogram (the average of the four recovery scenarios described above, considering the 85-percent reduction efficiency), this option is associated with a cost savings of approximately $13.71 per job.
- **Emissions Reductions.** Under the refrigerant recovery option described above, the emissions of 0.83 kilogram of refrigerant can be avoided from small equipment, resulting in the reduction of approximately 1.38 tCO_2eq per recovery job (assuming an average GWP of 1,664).[4]

Cost and Emissions Reduction Analysis for Distributed Systems

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for distributed systems, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** HFC-distributed systems are assumed to cost 5 percent more than conventional HFC centralized DX systems (IPCC, 2005). For a large (60,000 square foot) supermarket, this cost is estimated to translate to an additional $7,200.[5]
- **Annual Costs.** It is assumed that this option consumes 5 percent more energy than conventional DX systems (IPCC, 2005), where it is assumed that conventional DX systems consume 1,200,000 kilowatt hours each year (ADL, 2002). Thus, at an average electricity price of approximately $0.05 per kilowatt hour (USEIA, 2005), this option is associated with an annual incremental cost of approximately $2,796 for a large supermarket. In all other countries, this annual cost was adjusted by average country- or region-specific electricity prices (i.e., average of 1994 through 1999) based on USEIA data (2000).
- **Cost Savings.** This system is estimated to prevent 90 percent of direct annual emissions, as a result of a 75-percent reduction in charge size and a reduction in annual leakage rate to just 6

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[3] This assumes that the price of R-134a is $16.01 per kilogram, that R-404A is $16.15 per kilogram, and that R-407C is $19.09 per kilogram (Baker Distributing, 2005). Pricing is based on 24- to 30-pound cylinders, not bulk purchase. The average cost was calculated based on an average refrigerant cost used in the four scenarios, where only R-134a is recovered from MVACs at service and disposal, and where R-134a, R-404A, and R-407C are all recovered from stationary equipment at service and disposal.

[4] This GWP value is based on an average GWP for HFCs used in MVACs and stationary equipment, where the average GWP for HFCs used in MVACs is assumed to be 1,300 (R-134a), and the average GWP for HFCs used in stationary equipment is assumed to be 2,028.5 (R-134a, R-404A, and R-407C). Therefore, the calculation is [1,300 + (1,300 + 3,260 + 1,525.5) / 3] / 2 = 1,664.25.

[5] This assumes that conventional DX systems cost $144,000 for a 60,000 square foot supermarket. This assumption is based on the following data points: 3,600 pounds of refrigerant are needed to charge a DX systems for a 60,000 square foot supermarket (ADL, 2002); 5 pounds of refrigerant are needed per ton of cooling capacity; and DX systems typically cost approximately $200 per ton of cooling capacity installed, thus 3,600 / 5 = 720 × $200 = $144,000 capital cost for DX (USEPA, 2001a).

percent[6] (IPCC, 2005). Therefore, as a result of reduced leakage, a large supermarket is estimated to save 220 kilograms of refrigerant each year.[7] Assuming an average cost (R-404A) of $16.15 per kilogram (Baker Distributing, 2005),[8] an annual refrigerant cost savings will equal approximately $3,560 per supermarket.

- **Emissions Reductions.** The reduction of direct emissions of approximately 220 kilograms of refrigerant equals approximately 719 tCO_2eq per supermarket per year. Furthermore, as a result of avoided losses at disposal (assuming that, as with the DX system, on average 56 percent of the original charge is emitted at disposal), a further 686 kilograms of refrigerant emissions could be avoided per supermarket, equal to a one-time emissions reduction of approximately 2,236 tCO_2eq per supermarket.[9]

  However, because the distributed system described above uses 5 percent more energy than a typical DX system, more CO_2 is produced in generating an additional 60,000 kilowatt hours per year to run the system.[10] This indirect energy penalty is calculated to be approximately 36 tCO_2eq per large supermarket each year, using average power plant emissions rates in the United States (of 0.606 kilogram CO_2 per kilowatt hour) (USEIA, 2004). In all other countries, the indirect emissions penalty was calculated by multiplying the 36 tCO_2eq emissions penalty calculated for the United States by a ratio of U.S. to regional or national average CO_2 emissions rates for electricity production, based on IPCC (2005).

  Therefore, for the United States, the net annual emissions reduction associated with this option is approximately 682 tCO_2eq per supermarket (719 – 36), with an additional one-time reduction of 2,236 tCO_2eq at disposal.

Cost and Emissions Reduction Analysis for HFC Secondary Loop Systems

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for HFC secondary loop systems, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** This option is assumed to cost between 10 and 25 percent more than conventional centralized HFC DX systems (IPCC, 2005). For calculation purposes, 17.5 percent is

[6] This analysis assumes that for a 60,000 square foot supermarket, the baseline DX system has an annual leakage rate of 15 percent and a charge size of 1,633 kilograms (3,600 pounds) (ADL, 2002). The annual leakage rate of distributed systems is assumed to be reduced by 60 percent – so 6 percent annual leakage – and have a charge size of 25 percent that of a DX store – so approximately 408 kilograms (900 pounds).

[7] This estimate assumes that with a DX system, roughly 245 kilograms are emitted each year (1,633 kg × 0.15 = 245 kg) (ADL, 2002); thus, given the reduction in charge size and leakage rate, approximately 220 kilograms of refrigerant emissions can be avoided: [245 – (1,633 × 0.25 × 0.06)] = 220 kg.

[8] Price is based on a 24-pound cylinder, not bulk purchase.

[9] This assumes an initial refrigerant charge of 3,600 pounds (1,633 kilograms) for DX systems and only 900 pounds (408 kilograms) for distributed systems (ADL, 2002). Therefore, if 56 percent of the original charge is emitted at disposal, an additional 686 kilograms of refrigerant emissions can be avoided with distributed systems compared to DX systems [(1633 kg × 56%) – (408 kg × 56%) = 686 kg].

[10] This assumes that a conventional DX system used in a 60,000 square foot supermarket requires 1,200,000 kilowatt hours per year to operate (ADL, 2002). Therefore, the calculation used here is 1,200,000 × 0.05 = 60,000.

assumed. For a large (60,000 square foot) supermarket, this cost is estimated to translate to an additional $25,200.[11]

- **Annual Costs.** This option is assumed to consume 10 percent more energy than conventional DX systems (IPCC, 2005). Thus, for a large supermarket, this option is associated with an annual cost of approximately $5,592, assuming that a conventional DX system consumes 1,200,000 kilowatt hours each year (ADL, 2002), at an average electricity price of approximately $0.05 (USEIA, 2005). In all other countries, this annual cost was adjusted by country- or region-specific average electricity prices (i.e., average of 1994 through 1999 prices), based on USEIA data (2000).
- **Cost Savings.** Secondary loop systems are assumed to reduce annual direct emissions by approximately 93 percent for large supermarkets as a result of charge size reductions of 80 percent and an annual leakage rate of 5 percent (IPCC, 2005). As a result of reduced leakage, it is estimated that 229 kilograms of refrigerant will be saved each year.[12] Assuming an average cost of (R-404A) refrigerant of $16.15 per kilogram (Baker Distributing, 2005),[13] an annual cost savings will equal approximately $3,692 per supermarket.
- **Emissions Reductions.** The annual avoidance of 229 kilograms of refrigerant emissions equates to approximately 745 tCO_2eq per supermarket. Furthermore, as a result of avoided losses at disposal (assuming that, as with DX systems, an average 56 percent of the original charge is emitted at disposal), a further 732 kilograms of refrigerant emissions could be avoided per supermarket, equal to a one-time emissions reduction of approximately 2,385 tCO_2eq per supermarket [(1,633 × 0.56) – (1,633 × 0.2 × 0.56) = 732 kilograms].

  However, because the secondary loop system described above uses more energy than a typical DX system, more CO_2 is produced in generating electricity to run the system. As mentioned above, this option is assumed to consume 10 percent more energy than conventional DX systems, or an additional 120,000 kilowatt hours per year.[14] This indirect energy penalty is calculated to be approximately 73 tCO_2eq per large supermarket each year, using average power plant emissions rates in the United States of 0.606 kilogram CO_2 per kilowatt hour (USEIA, 2004). In all other countries, the indirect emissions penalty was calculated by multiplying the 73 tCO_2eq emissions penalty calculated for the United States by a ratio of U.S. to regional or national average CO_2 emissions rates for electricity production, based on IPCC (2005).

  Therefore, in the United States, the net annual emissions reduction associated with this option is estimated to be approximately 673 tCO_2eq per supermarket (745 – 73), with an additional one-time reduction of 2,385 tCO_2eq at disposal.

Cost and Emissions Reduction Analysis for Ammonia Secondary Loop Systems

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for ammonia secondary loop systems, the results of which are presented in Section IV.2.4.

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[11] Cost is calculated using assumptions presented previously.

[12] Based on the baseline assumptions for DX systems presented previously, this estimate is calculated as follows: (1,633 kg × 0.15) – (1,633 × 0.2 × 0.05) = 229 kg.

[13] Price is based on a 24-pound cylinder, not bulk purchase.

[14] See baseline assumption for DX energy consumption provided previously. The calculation used here is 1,200,000 kWh/yr × 10% = 120,000 kWh/yr.

- **One-Time Costs.** Ammonia secondary loop systems are assumed to cost 25 percent more than conventional centralized HFC direct expansion systems (IPCC, 2005). For a large (60,000 square foot) supermarket, this cost translates roughly to an additional $36,000.[15]
- **Annual Costs.** This option is assumed to consume 10 percent more energy than conventional DX systems (IPCC, 2005). Thus, for a large supermarket, this option is associated with an annual cost of $5,592, assuming that a conventional DX system consumes 1,200,000 kilowatt hours each year (ADL, 2002), at an average electricity price of approximately $0.05 (USEIA, 2005). In all other countries, this annual cost was adjusted by country- or region-specific average electricity prices (i.e., average of 1994 through 1999 prices), based on USEIA data (2000).
- **Cost Savings.** Given that this system will prevent 100 percent of direct annual HFC emissions, for a large supermarket, it is estimated that 245 kilograms of refrigerant will be saved each year as a result of reduced leakage.[16] Assuming an average cost of (R-404A) refrigerant of $16.15 per kilogram (Baker Distributing, 2005),[17] this translates into annual cost savings of approximately $3,955 per supermarket.
- **Emissions Reductions.** The reduction of approximately 245 kilograms of refrigerant equates to approximately 799 tCO_2eq in direct emissions reduced per supermarket per year. Furthermore, as a result of avoided HFC losses at disposal (assuming that, on average 56 percent of the original DX charge would have been emitted at disposal), a further 914 kilograms of refrigerant emissions could be avoided per supermarket, equal to a one-time emissions reduction of approximately 2,981 tCO_2eq per supermarket (1,633 × 0.56 = 914 kg).

  However, because the ammonia secondary loop system uses more energy than a typical DX system, more CO_2 is produced in generating electricity to run it. As mentioned above, this option is assumed to consume 10 percent more energy than conventional DX systems, or an additional 120,000 kilowatt hours.[18] This indirect energy penalty is calculated to be approximately 73 tCO_2eq per large supermarket each year, using average power plant emissions rates in the United States of 0.606 kilogram CO_2 per kilowatt hours (USEIA, 2004). In all other countries, the indirect emissions penalty is calculated by multiplying the 73 tCO_2eq emissions penalty calculated for the United States by a ratio of U.S. to regional or national average CO_2 emissions rates for electricity production, based on IPCC (2005).

  Therefore, in the United States, the net annual emissions reduction associated with this option is estimated to be 726 tCO_2eq per supermarket (799 – 73 = 726), with an additional one-time reduction of 2,981 tCO_2eq at disposal.

Cost and Emissions Reduction Analysis for Enhanced HFC-134a MVACs

The following describes the cost and emissions inputs—compared to the business-as-usual HFC-134a baseline—used to derive the final dollars per tCO_2eq for enhanced HFC-134a systems for MVACs, the results of which are presented in Section IV.2.4.

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[15] Cost is calculated using assumptions presented previously.

[16] Values are calculated using assumptions presented previously (DX charge size of 1,633 kg and annual leak rate of 15%).

[17] Price is based on a 24-pound cylinder, not bulk purchase.

[18] This assumes that a conventional DX system used in a 60,000-square-foot supermarket requires 1,200,000 kilowatt hours per year to operate (ADL, 2002). Therefore, the calculation used here is 1,200,000 × 0.10 = 120,000.

- **One-Time Costs.** While enhanced HFC-134a MVACs are yet to be fully developed and commercialized, the additional capital cost of this option is assumed to be €40 or $42.12 USD,[19] per system, based on SAE (2003a).
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Enhanced HFC-134a systems will potentially reduce energy consumption by as much as 25 to 30 percent (SAE, 2003a). For calculation purposes, 27.5 percent is assumed. In the United States, this gain in energy efficiency is estimated to translate into a savings of 10.2 gallons of gasoline per vehicle per year (Rugh and Hovland, 2003). Assuming an average 2005 gasoline price of $2.02 per gallon (USEIA, 2006), this results in an annual cost savings of approximately $20.69 per year in the United States.[20] For all other countries, this annual cost savings is adjusted by the estimated amount of gasoline saved per vehicle per year[21] and by average regional costs of unleaded gasoline.[22]

  In addition, cost savings are also associated with saved HFC-134a refrigerant, assumed to cost $16.01 per kilogram (Baker Distributing, 2005).[23] On an annual basis, these savings are estimated to total approximately $0.70 per MVAC—assuming that conventional HFC-134a MVACs contain an average charge of 0.8 kilogram, that they emit 10.9 percent of this charge each year, and that 50 percent of these emissions could be avoided through this option. While this analysis includes the savings from lower refrigerant leakage, it does not include the savings from the service event. Additional savings may be realized if less service events are required.
- **Emissions Reductions.** Under the enhanced HFC-134a system described above, the annual emissions of approximately 0.04 kilogram (i.e., 0.8 kilogram charge multiplied by the emissions rate of 10.9 percent per year and the reduction efficiency of 50 percent) of HFC-134a refrigerant could be avoided from reduced leakage, resulting in the annual reduction of 0.06 tCO_2eq per MVAC.

  In addition, indirect emissions benefits will be realized as a result of improved system efficiency. Based on U.S. emissions factors for motor gasoline (USEPA, 2003), indirect emissions benefits

[19] This cost conversion is based on an exchange rate of $112.5/€100 (Universal Currency Converter Web site, 2003), deflated to 2000 dollars. The 2003 conversion rate is used because the capital cost estimate was made in that year.

[20] Average gasoline price is based on the reported national average retail price of regular gasoline in 2005 in the United States, deflated to 2000 dollars (USEIA, 2006). To the extent that gasoline prices—which are highly volatile—change, so too will the cost savings of this option.

[21] The estimated quantity of gasoline saved per vehicle per year varies by the percentage of fuel consumed by MVACs (as a percentage of total fuel consumption), which in turn varies by MVAC usage. Based on available data, the estimated annual savings of gasoline per vehicle per year associated with a 27.5-percent increase in MVAC efficiency is 2.3 gallons in Europe and 2.0 gallons in Japan (Rugh and Hovland, 2003). For this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

[22] 2003 gasoline prices were used to adjust regional costs in non-U.S. countries, since more recent pricing data were not widely available for other countries. Specifically, the following prices (presented in 2000 dollars), based on USEIA (2005), and country proxies are used by calculating the ratio of the given price to that shown for the U.S.: average price in Germany ($4.30 per gallon) is used as a proxy for all European countries; the average price in Australia and Canada ($1.96 per gallon) is used as a proxy for all other developed countries except Japan; and the average price in Mexico and Taiwan ($1.99 per gallon) is used as a proxy for all developing countries. The average gasoline price for Japan is $3.25 per gallon. The average 2003 gasoline price in the United States is $1.49 (in 2000 dollars).

[23] Price is based on a 30-pound cylinder, not bulk purchase.

associated with an efficiency improvement of 27.5 percent could lead to the annual reduction of 10.2 gallons of gasoline, or an additional 0.09 tCO_2eq per MVAC in the United States.[24] For all other countries, the annual indirect emissions benefit estimated for the United States (0.09 tCO_2eq) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emissions factor for motor gasoline (IPCC, 1996).

Therefore, the net annual emissions reduction associated with this option is 0.15 tCO_2eq per MVAC in the United States (0.06 + 0.09 = 0.15).

Cost and Emissions Reduction Analysis for HFC-152a MVACs

The following describes the cost and emissions inputs—compared to the business-as-usual HFC-134a baseline—used to derive the final dollars per tCO_2eq for HFC-152a systems for MVACs, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** While research and development is still ongoing on HFC-152a systems, based on the latest available industry estimates, the capital cost of this option is assumed to be 20 to 25 Euros per system more than a standard HFC-134a system (SAE, 2003a). For calculation purposes, 22.50 €, or $23.69,[25] is used. Due to flammability concerns, it is possible that a separate/additional garage space may be needed to service HFC-152a MVACs in isolation from sparking devices and any welding or cutting activities. However, sparking devices are used and welding/cutting activities are currently performed in garages despite the use of other flammable fluids, such as gasoline and lubricants. Therefore, no capital costs associated with separate or additional garage space are included in this analysis
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Based on industry consensus, HFC-152a systems are estimated to reduce energy consumption by 10 percent (SAE, 2003a), although these gains may not be realized in all weather conditions (Hill and Atkinson, 2003). This gain in energy efficiency is estimated to result in a savings of approximately 3.9 gallons of gasoline per vehicle per year in the United States, which translates into an annual cost savings of $7.92, based on average U.S. prices of regular unleaded gasoline in 2005 (Rugh and Hovland, 2003; USEIA, 2006). For all other countries, this cost savings is adjusted by the estimated amount of gasoline saved per vehicle per year[26] and by the average regional costs of unleaded gasoline.[27]

[24] Using a motor gasoline emissions factor of 19.36 pounds of CO_2 per gallon (USEPA, 2003), the annual savings of approximately 10.2 gallons of gasoline in the United States results in a savings of 198.25 pounds of CO_2 per year, which is equal to 0.09 tCO_2eq (198.25 / 2.205 / 1,000 = 0.09).

[25] This cost conversion is based on an exchange rate of $112.5/€100 (Universal Currency Converter Web site, 2003), deflated to 2000 dollars. The 2003 conversion rate is used because the capital cost estimate was made in that year.

[26] It is assumed that a 10 percent increase in MVAC efficiency results in the annual savings of 0.8 gallons of gasoline in Europe and 0.7 gallons of gasoline in Japan (Rugh and Hovland, 2003). For the purpose of this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

[27] Annual cost savings are adjusted by 2003 average gasoline prices, as explained in footnote 22. To the extent that gasoline prices—which are highly volatile—change, so too will the cost savings of this option.

Because this analysis assumes that HFC-152a would be the same price as HFC-134a,[28] and because HFC-152a systems are assumed to leak at the same rate as conventional HFC-134a systems (although the associated emissions are less damaging to the environment because of the lower GWP), no cost savings are associated with saved refrigerant.

- **Emissions Reductions.** Under the HFC-152a system described above, the annual emissions of approximately 0.09 kilogram of HFC-134a refrigerant could be avoided and replaced by annual emissions of 0.09 kilogram of HFC-152a, which results in the annual reduction of 0.10 tCO_2eq per MVAC. Direct emissions benefits are also achieved by this option at MVAC disposal, as the emissions of HFC-134a could be substituted by emissions of lower-GWP HFC-152a. Assuming that, on average, 42.5 percent of the original MVAC charge is lost at disposal, the one-time loss of 0.34 kilogram of HFC-134a refrigerant could be replaced by HFC-152a, resulting in the one-time reduction of approximately 0.39 tCO_2eq per MVAC at end of life.

  In addition, indirect emissions benefits will also be realized as a result of improved system efficiency. Based on U.S. emissions factors for motor gasoline (USEPA, 2003), indirect emissions benefits associated with a 10-percent system efficiency improvement could lead to the annual reduction of 3.9 gallons of gasoline, or an additional 0.03 tCO_2eq per MVAC in the United States.[29] For all other countries, the annual indirect emissions benefit estimated for the United States (0.03 tCO_2eq) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emissions factor for motor gasoline (IPCC, 1996).

  Therefore, the net annual emissions reduction associated with this option is approximately 0.14 tCO_2eq per MVAC in the United States (0.10 + 0.03), with an additional one-time reduction of 0.39 tCO_2eq at disposal.

Cost and Emissions Reduction Analysis for CO_2 MVACs

The following describes the cost and emissions inputs—compared to the business-as-usual HFC-134a baseline—used to derive the final dollars per tCO_2eq for CO_2 systems for MVACs, the results of which are presented in Section IV.2.4.

- **One-Time Costs.** Based on SAE (2003a), the capital cost of this option is assumed to be 80 to 120 Euros on a per system basis. For calculation purposes, 100 €, or $105.30,[30] was used.
- **Annual Costs.** No annual costs are associated with this option.
- **Cost Savings.** Based on industry consensus, it is estimated that enhanced CO_2 systems may reduce energy consumption compared to a baseline HFC-134a system by 20 to 25 percent (an average of 22.5 percent is used for calculation purposes), although these gains may not be realized at all ambient temperatures (SAE, 2003a). This gain in energy efficiency results in the savings of approximately 8.4 gallons of gasoline per vehicle per year in the United States, which

[28] In this scenario, where MVACs would create a much larger demand for HFC-152a, it is assumed that HFC-152a will be the same price as HFC-134a.

[29] Using a motor gasoline emissions factor of 19.36 pounds of CO_2 per gallon (USEPA, 2003), the annual savings of 3.9 gallons of gasoline in the United States results in a savings of 75.91 pounds of CO_2 per year, which is equal to 0.03 tCO_2eq (75.91 / 2.205 / 1,000 = 0.03).

[30] This cost conversion is based on an exchange rate of $112.5/€100 (Universal Currency Converter Web site, 2003), deflated to 2000 dollars. The 2003 conversion rate is used because the capital cost estimate was made in that year.

translates into an annual cost savings of roughly $16.95 (Rugh and Hovland, 2003; USEIA, 2006). For all other countries, this cost savings was adjusted by the estimated amount of gasoline saved per vehicle per year[31] and by the average cost of unleaded gasoline (Rugh and Hovland, 2003; USEIA, 2005).[32]

In addition, cost savings are associated with saved (HFC-134a) refrigerant, assumed to cost $16.01 per kilogram (Baker Distributing, 2005).[33] On an annual basis, these savings are estimated to total $1.40 per MVAC, assuming that conventional HFC-134a MVACs contain an average charge of 0.8 kilogram, that they emit 10.9 percent of this charge each year, and that 100 percent of these emissions could be avoided through this option. The additional cost of CO_2 refrigerant is assumed to be negligible and is not included in the analysis.

- **Emissions Reductions.** Under the CO_2 system described above, the annual emissions of approximately 0.09 kilogram of HFC-134a refrigerant could be avoided, resulting in the reduction of 0.11 tCO_2eq per MVAC. Furthermore, assuming a disposal loss rate of 42.5 percent, a one-time disposal loss of 0.34 kilogram of HFC-134a refrigerant can also be avoided, which would result in a further one-time reduction of 0.44 tCO_2eq per MVAC.

  In addition, indirect emissions benefits will be realized as a result of improved system efficiency. Based on U.S. emissions factors for motor gasoline (USEPA, 2003), indirect emissions benefits associated with a 22.5-percent system efficiency improvement could lead to the annual reduction of 8.4 gallons of gasoline, or an additional 0.07 tCO_2eq per MVAC in the United States.[34] For all other countries, the annual indirect emissions benefit estimated for the United States (0.07 tCO_2eq) was adjusted by the estimated amount of gasoline saved per vehicle per year (Rugh and Hovland, 2003) and by the global average emissions factor for motor gasoline (IPCC, 1996).

  Therefore, the net annual emissions reduction associated with this option is approximately 0.19 tCO_2eq per MVAC in the United States (0.11 + 0.07), with an additional one-time reduction of 0.44 tCO_2eq at disposal.

[31] A 22.5-percent increase in MVAC efficiency is assumed to result in the annual savings of 1.9 gallons of gasoline in Europe and 1.7 gallons of gasoline in Japan (Rugh and Hovland, 2003). For the purpose of this report, the MVAC efficiency value for Europe was used as a proxy for the remaining countries.

[32] Annual cost savings are adjusted by average 2003 gasoline prices, as explained previously. To the extent that gasoline prices—which are highly volatile—change, so too will the cost savings of this option.

[33] Price is based on a 30-pound cylinder, not bulk purchase.

[34] Using a motor gasoline emissions factor of 19.36 pounds of CO_2 per gallon (USEPA, 2003), the annual savings of 8.4 gallons of gasoline in the United States results in a savings of 162.47 pounds of CO_2 per year, which is equal to 0.07 tCO_2eq (162.47 / 2.205 / 1,000 = 0.07).

F.1 Abatement Option Summary Tables

Table F-1: Refrigeration and Air-Conditioning Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Direct Emissions Reduction ($MtCO_2eq$)	Indirect Emissions Reduction ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
Leak Repair	–$4.10	–$4.10	2.08	0.00	0.6%	2.08	0.6%
Recovery (REFRIG)	–$2.62	–$2.62	11.42	0.00	3.2%	13.50	3.8%
Replace DX with Distributed System	–$1.08	$9.99	6.05	–0.07	1.7%	19.56	5.5%
Enhanced HFC-134a in MVACs	–$175.92	$16.21	2.90	3.27	0.8%	22.46	6.3%
HFC-152a in MVACs	–$27.59	$18.18	0.17	0.08	0.0%	22.62	6.3%
Ammonia Secondary Loop	$6.33	$26.40	3.33	–0.43	0.9%	25.95	7.3%
Secondary Loop	$4.81	$26.70	4.97	–0.16	1.4%	30.92	8.7%
CO_2 for New MVACs	$7.57	$91.60	0.85	0.09	0.2%	31.77	8.9%

Table F-2: Refrigeration and Air-Conditioning Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Direct Emissions Reduction ($MtCO_2eq$)	Indirect Emissions Reduction ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
Leak Repair	–$4.10	–$4.10	4.91	0.00	0.8%	4.91	0.8%
Recovery (REFRIG)	–$2.62	–$2.62	40.16	0.00	6.4%	45.07	7.2%
Replace DX with 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%
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%

Appendix G: Cost and Emissions Reduction Analysis for Options to Abate International HFC, HFE, and PFC Emissions from Solvents

Cost and Emissions Reduction Analysis for Conversion to HFE Solvents

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for converting to an HFE solvent, the results of which are presented in Section IV.3.4.

- **One-Time Costs.** HFE solvents are very similar to HFC-4310mee in their key chemical properties, such that existing equipment designed with low emissions features can still be used with HFE solvents, although the equipment might need minor adjustments, such as resetting of the heat balance. These modifications are not likely to amount to a substantial one-time cost (ICF Consulting, 2003; 3M Performance Materials, 2003); therefore, this analysis assumes no one-time costs for converting to an HFE solvent.
- **Annual Costs.** According to industry experts, HFE solvents have pricing structures roughly equal to the pricing structure of HFCs (3M Performance Materials, 2003). Therefore, this analysis assumes no annual costs are incurred when transitioning to an HFE solvent.
- **Cost Savings.** This analysis does not assume a cost savings. A net cost savings may occasionally be experienced by end-users that choose HFE solvents that are lower in density than HFC-4310mee. For example, since the same volume of solvent is used and solvents are sold on a mass basis, formulations blended with HFE-7200 may be lower in cost relative to formulations containing HFC-4310mee (3M Performance Materials, 2003). Long-term savings may be realized when this option is combined with equipment retrofitting, consequently reducing the costs per item cleaned. These potential cost savings are not analyzed here.
- **Emissions Reductions.** For the purpose of this analysis, a one-to-one mass ratio of HFC-4310mee to an HFE alternative solvent is assumed. Therefore, for every one kilogram of HFC-4310mee avoided, the use of HFE solvent is estimated to reduce emissions by 0.99 metric tons of carbon dioxide equivalent (tCO_2eq) (i.e., 1 kilogram or 0.001 metric tons of solvent multiplied by the GWP of 1300 and a reduction efficiency of 0.764).

Cost and Emissions Reduction Analysis for Improved Equipment and Cleaning Processes Using Existing Solvents (Retrofit)

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for the retrofit option, the results of which are presented in Section IV.3.4.

- **One-Time Costs.** The cost of retrofitting modern or high-quality batch cleaning equipment ranges from $11,200 to $16,800 for small units, to approximately $18,600 or more for larger units. This report conservatively assumes that a $16,800 investment is required to retrofit a vapor degreaser with a 13-square-foot open-top area (Durkee, 1997).
- **Annual Costs.** This analysis assumes no annual labor costs. However, good handling practices, such as employee training and regular maintenance to reduce the risk of leaks, are encouraged for retrofitted equipment. These practices would likely lead to an increase in operating costs (UNEP, 2003).
- **Cost Savings.** According to experts, HFC users that retrofit their equipment will likely experience a drop in solvent costs per operating hour. The cost savings will depend on the size of the cleaner and the specific solvent conservation features installed. To account for cost savings in the model,

the estimated cost of HFC-4310mee ($45.00 per kilogram) was used to represent the value of the solvent per kilogram saved through retrofitting (ICF Consulting, 2003). The example from Durkee (1997) that reports the emissions reduction of 70 percent estimates that 4,898.4 pounds, or 2,221.9 kilograms, of solvent were still emitted from the retrofitted cleaner. Thus, it is estimated that 5,184 kilograms (i.e., 2,221.9 kilograms divided by 30 percent yields the total cleaner's mass of 7,406.3 kilograms; a reduction of 70 percent is thus equal to 5,184 kilograms) of solvent per year can be avoided for a 13-square-foot unit. This savings equates to close to $235,000 per year. Hence, investments in retrofit options frequently provide a profitable return for the end-user.

- **Emissions Reductions.** Assuming a retrofit on a vapor degreaser with an open-top area 13 square feet in size, annual emissions avoided are estimated to be 5,184 kilograms of the high GWP solvent (7,406.3 kilograms multiplied by a reduction efficiency of 0.7) (Durkee, 1997), or 0.0045 $MtCO_2eq$ (i.e., 5.184 metric tons HFC avoided, multiplied by the GWP of 873.7, representing the weighted average of high-GWP gas solvent emissions projected for 2020 in the United States, divided by 1 million). The Durkee (1997) data used for this analysis are consistent with industry experience. For example, one anonymous user reduced annual emissions by close to 3,500 kilograms after retrofitting two solvent cleaners of 27 and 42 gallon capacities (roughly equivalent to vapor degreasers with an open-top area 5 to 7 square feet in size) (Ultrasonics, 2002).

Cost and Emissions Reduction Analysis for Aqueous and Semiaqueous NIK Replacement Alternatives

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for the aqueous and semiaqueous cleaning options, the results of which are presented in Section IV.3.4.

- **One-Time Costs.** This cost analysis assumes that the incremental investment required to convert to a typical NIK process is approximately $80,000 for aqueous cleaning and $10,000 for semiaqueous cleaning (ICF Consulting, 1992).
- **Annual Costs.** Annual increased operating costs are dependent on a variety of factors, including the cost of the cleaning chemicals, electricity and/or other utilities, and the specific parts being cleaned. In general, energy-intensive rinsing and drying processes, wastewater treatment, and effluent monitoring can add to the cost of aqueous and semiaqueous processes. Semiaqueous cleaning carries more operating costs associated with additional steps of separating and cleaning two waste streams—the water and the semiaqueous solvent solution (UNEP, 1999a). Because cost savings have yet to be quantified for this analysis, which may offset increased operating costs, this analysis does not assume annual costs for NIK options; however, future work could be performed to investigate annual costs and cost savings realized.
- **Cost Savings.** Because of the potential complexity of the process, this report assumes no cost savings for NIK technologies; however, many companies that have installed NIK systems have realized long-term cost savings because annual solvent expenditures are significantly reduced (Chaneski, 1997).
- **Emissions Reductions.** This analysis assumes that when converting to either NIK process, annual emissions avoided for a standard unit are 3,494 kilograms (ICF Consulting, 1992). Assuming an average mix of high-GWP solvents avoided, this reduction equates to 0.003 $MtCO_2eq$ for semiaqueous and aqueous cleaning. This calculation is based on a GWP of 873.70, which is a weighted average of high-GWP gas solvent emissions projected for 2020 in the United States. Because of the likely high variability experienced and a lack of specific information on increased drying needs for NIK processes, the additional emissions from any potential additional energy use are not included as an offset to the estimated emissions reductions.

G.1 Abatement Option Summary Tables

Table G-1: Solvents Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO_2eq)	% Reduction from 2010 Baseline	Running Sum of Reductions (MtCO_2eq)	Cum. % Reduction from 2010 Baseline
	Low	High				
Retrofit	–$50.75	–$50.75	0.1299	1.7%	0.13	1.7%
HFC to HFE	$0.00	$0.00	0.67	8.7%	0.80	10.4%
NIK Semi-Aqueous	$0.67	$0.67	0.34	4.5%	1.14	14.8%
NIK Aqueous	$5.36	$5.36	0.69	8.9%	1.83	23.7%

Table G-2: Solvents Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO_2eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO_2eq)	Cum. % Reduction from 2020 Baseline
	Low	High				
Retrofit	–$50.75	–$50.75	0.0454	1.0%	0.05	1.0%
HFC to HFE	$0.00	$0.00	1.11	24.7%	1.16	25.7%
NIK Semi-Aqueous	$0.67	$0.67	0.35	7.7%	1.51	33.4%
NIK Aqueous	$5.36	$5.36	0.70	15.5%	2.20	48.9%

Appendix H: Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Foams

Replacing HFC-134a with HCs in Continuous and Discontinuous Panel Foam

Table H-1: Base Case Assumptions for a Contractor Using HFC-134a in PU Continuous and Discontinuous Panel Foam

Variable	Value	Source
Blowing agent component of foam	8.7%	Cannon, 2001
Blowing agent consumption	1,048,600 lbs	UNEP, 2002a
Foam produced	12,052,874 lbs	Calculation[a]
Original foam cost	$0.924/lb	Calculation[b]
Price of HFC-134a	$2.45/lb[c]	Diversified CPC, 2006 and expert opinion

[a] See text.

[b] Average of five data points based on confidential information obtained for this report.

[c] For the purpose of this analysis, the cost of HFC-134a used in foams is assumed to equal the cost of HFC-134a bought in bulk, which ranges from $3.30 to $3.60 per pound as provided by Diversified CPC (2006). However, based on the historical as well as anticipated fluctuations in HFC-134a global pricing, this analysis assumes an approximate cost of $2.45 per pound. Note that this price is lower than that seen when buying smaller quantities, e.g., for servicing refrigeration and air conditioning systems. Historically, global capacity of HFC-134a was underused for several years, yielding depressed global pricing for HFC-134a. In 2003, strong global demand drove the market price of HFC-134a to $3.50 per pound. This price is expected to stay stable until at least 2007, when, as a result of potential new Asian capacity and reduced European consumption resulting from a ban on its use in mobile air conditioners in Europe beginning in 2011, the price is estimated to drop to about $2.75 per pound ($2.45 in 2000 dollars).

Table H-2: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-134a with HCs in PU Continuous and Discontinuous Panel Foam

Variable	Value	Source
Capital Costs	$273,473	Assumption
Fire Retardant Use		
Incremental increase in fire retardant use	3%	Assumption
Cost of fire retardant	$1.89/lb	Exxon, 2004
Increase in Foam Density	12%	ICF Consulting, 2004
Assumed Increase in Cost of Foam	$0.10/lb	Assumption
Alternative Foam Cost	$1.024/lb	Calculation
Training[a]		
Training class costs	$3,646	ICF Consulting, 2004
Days per training class	14 days	ICF Consulting, 2004
Number of workers	8 workers	ICF Consulting, 2004
Days of training needed by each worker	5 days/year	ICF Consulting, 2004
Blowing Agent Substitution Ratio	1.42	Assumption
Price of Pentane	$0.546/lb	Exxon, 2004

[a] Assumes a cost of approximately $2,735 to $4,558 per training class, 6 to 10 employees, and 4 to 6 days of training annually per worker.

Cost and Emissions Reduction Analysis for Replacing HFC-134a with HCs in Continuous and Discontinuous Panel Foam

- **One-Time Costs.** According to industry experts, the one-time cost associated with this abatement option is the cost of installing safety (e.g., non-sparking) equipment. For this purpose, a one-time cost of $273,473 was assumed for replacing HFC-134a with HCs.
- **Annual Costs.** This analysis assumes increased operating costs of $2,175,424 for this abatement option. These costs result from fire retardant use, changes in foam density, and HC safety training for workers. Data on other additional costs that may be incurred (e.g., longer fasteners) were not readily available and are not included in this analysis. Costs associated with fire retardant use are $683,948,[1] calculated as the amount of foam produced (12,052,874 pounds) multiplied by the incremental increase in fire retardant used in foam (3 percent) and the fire retardant costs ($1.89 per pound). Worker training costs are estimated to be $10,418, calculated by multiplying the costs of training per day by the number of workers and the number of training days (i.e., costs per day = $3,646.31/14 days = $260.45/day; total cost per year = $260.45/day × 5 days × 8 workers = $10,418). Costs associated with foam density increases are $1,481,057, calculated by multiplying the amount of foam produced (12,052,874 pounds) by alternative foam costs ($1.024 per pound) and the increase in foam density (12 percent). The alternative foam cost is the original foam cost (an average of five data points based on confidential information obtained for this report) plus the assumed increase in foam cost.
- **Cost Savings.** Because HCs are less expensive per kilogram than HFC-134a, there is a $2,164,154 per year cost savings associated with this option. Costs of the HFC blowing agents are $2,567,809 per year, while costs of alternative blowing agent are $403,656 per year. HFC costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent (1,048,600 lb × $2.45/lb = $2,567,809). The calculation of alternative blowing agent costs is the per-pound cost of alternative blowing agent ($0.546 per pound), multiplied by the amount of blowing agents used (1,048,600 pounds), and divided by the blowing agent substitution ratio (1.42). The blowing agent substitution ratio is assumed to be the molecular weight of HFC-134a (102 g/mole) divided by the molecular weight of pentane (72 g/mole).
- **Emissions Reductions.** This analysis estimates that by replacing HFCs-134a with HCs in this scenario, 0.62 $MtCO_2eq$ of the high-GWP gas that would have been emitted from foam manufactured by the hypothetical contractor during the lifetime of the foam produced in a given year is eliminated (1,048,600 lb × 0.4536 kg/lb × 1 Mt/1,000,000,000 kg × 1,300 = 0.62 $MtCO_2eq$).

[1] Note that many of the assumptions are presented in this report as rounded values. Calculations are performed using the actual values and then results are often reported also in rounded values.

One-Component Foam

Table H-3: Base Case Assumptions for a Contractor Using HFC-134a and HFC-152a in One-Component Foam

Variable	Value	Source
Blowing Agent Component of Foam	8.7%	Cannon, 2001
Blowing Agent Consumption	288,000 lbs	ICF Consulting, 2004
Foam Produced	3,310,345 lbs	Calculation[a]
Price of HFC-134a	\$2.45/lb[b]	Diversified CPC, 2006 and expert opinion
Price of HFC-152a	\$1.54/lb	Diversified CPC, 2006

[a] See text.

[b] For the purpose of this analysis, the cost of HFC-134a used in foams is assumed to equal the cost of HFC-134a bought in bulk, which ranges from \$3.30 to \$3.60 per pound as provided by Diversified CPC (2006). However, based on the historical as well as anticipated fluctuations in HFC-134a global pricing, this analysis assumes an approximate cost of \$2.45 per pound. Historically, global capacity of HFC-134a was underused for several years, yielding depressed global pricing for HFC-134a. In 2003, strong global demand drove the market price of HFC-134a to \$3.50 per pound. This price is expected to stay stable until at least 2007, when, as a result of potential new Asian capacity and reduced European consumption resulting from a ban on its use in mobile air conditioners in Europe beginning in 2011, the price is estimated to drop to about \$2.75 per pound (\$2.45 in 2000 dollars).

Table H-4: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-134a with HCs in One-Component Foam

Variable	Value	Source
Capital Costs	\$341,841	ICF, 2004
Blowing Agent Substitution Ratio	2.0	Assumption
Fire Retardant Use		
Incremental increase in fire retardant use	4.5%	ICF, 2004
Cost of fire retardant	\$1.89	Exxon, 2004
Training		
Training costs	\$3,646	ICF, 2004
Days per training class	14 days	ICF, 2004
Number of workers trained	14 workers	ICF, 2004
Number of training days needed by each worker	3 days/year	ICF, 2004
Price of Propane	\$0.46 lb	Exxon, 2004
Price of Butane	\$0.46 lb	Exxon, 2004

Cost and Emissions Reduction Analysis for Replacing HFC-134a with HCs in One-Component Foam

- **One-Time Costs.** According to industry experts, the one-time costs for replacing HFC-134a with HCs are \$341,841, which includes the cost of installing safety equipment.
- **Annual Costs.** This analysis assumes increased operating costs of \$292,711 for this abatement option. These costs result from costs associated with fire retardant use and worker safety training costs associated with the use of HCs. Table H-3 and Table H-4 summarize the assumptions used. Costs associated with fire retardant use are \$281,772 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire retardant costs (3,310,345 lb × 4.5% × \$1.89/lb = \$281,772). Worker training costs are estimated to be \$10,939, calculated by multiplying the costs of training per day by the number of workers and

the number of training days (i.e., costs per day = \$3,646/14 days = \$260.45/day; total cost per year = \$260.45/day × 3 days × 14 workers = \$10,939).

- **Cost Savings.** Because propane and butane are less expensive on a per-pound basis than HFC-134a, a \$639,673 annual cost savings is associated with this option. Costs of the HFC-134a blowing agent are \$705,254 per year, while costs of alternative blowing agents are \$65,581 per year. HFC costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used (288,000 lb × \$2.45/lb = \$705,254/year). The calculation of alternative blowing agent cost is the per-pound cost of alternative blowing agent (\$0.46 per pound), multiplied by the amount of blowing agent used (288,000 pounds), and divided by the blowing agent substitution ratio (2.0). The blowing agent substitution ratio is assumed to be the molecular weight of HFC-134a (102 g/mole) divided by the molecular weight of a 50/50 mix of propane and butane ((44+58)/2=51 g/mole).
- **Emissions Reductions.** This analysis estimates that by replacing HFC-134a with HCs in this scenario, 0.16 $MtCO_2eq$ of the high-GWP gas that would have been emitted by this facility during the lifetime of the one-component foam produced in a given year is eliminated (288,000 lb × 0.4536 kg/lb × 1 Mt/1,000,000,000 kg × 1,300 = 0.16 $MtCO_2eq$).

One Component: Replacing HFC-152a with HCs

Table H-5: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-152a with HCs in One-Component Foam

Variable	Value	Source
Capital Costs	\$341,841	ICF, 2004
Blowing Agent Substitution Ratio	1.29	Assumption
Fire Retardant		
Incremental increase in fire retardant use	4.5%	ICF, 2004
Cost of fire retardant	\$1.89	Exxon, 2004
Training		
Training costs	\$3,646/training class	ICF, 2004
Days per training class	14 days	ICF, 2004
Number of workers trained	14 workers	ICF, 2004
Number of training days needed by each worker	3 days/year	ICF, 2004

Cost and Emissions Reduction Analysis for Replacing HFC-152a with HCs in One-Component Foam

- **One-Time Costs.** According to industry experts, the one-time costs for replacing HFC-152a with HCs are \$341,841, which includes the cost of installing safety equipment. Although some additional safety precautions already existed to handle the flammability of HFC-152a, they were minor in comparison to those necessary for a primary HC blowing agent system; therefore the capital cost is estimated to be the same as the switch from HFC-134a to HCs, which is \$341,841.
- **Annual Costs.** This analysis assumes operating costs of \$292,711 for this abatement option. These costs result from fire retardant use and worker safety training associated with the use of HCs. Table H-3 and Table H-5 summarize assumptions associated with this abatement option. Costs associated with fire retardant use are \$281,772 and are calculated as the amount of foam produced multiplied by the incremental increase in fire retardant used in foam and the fire

retardant costs (3,310,345lb × 4.5% × $1.89/lb = $281,772). Worker training costs are estimated to be $10,939, calculated by multiplying the costs of training per day by the number of workers and the number of training days (i.e., costs per day = $3,646.31/14 days = $260.45/day; total cost per year = $260.45/day × 3 days × 14 workers = $10,939).

- **Cost Savings.** Because propane and butane are less expensive per pound than HFC-152a, a $342,779 annual cost savings is associated with this option. Costs of the HFC-152a blowing agent are $444,429 per year, while costs of alternative blowing agent are $101,650 per year. HFC costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used (288,000 lb × $1.54/lb = $444,429/year). The calculation of alternative blowing agent cost is the per-pound costs of alternative blowing agent ($0.46 per pound), multiplied by the amount of blowing agent used (288,000 pounds), and divided by the blowing agent substitution ratio (1.29). The blowing agent substitution ratio is assumed to be the molecular weight of HFC-152a (66 g/mole) divided by the molecular weight of a 50/50 mix of propane and butane ((44+58)/2=51 g/mole).
- **Emissions Reductions.** This analysis estimates that by replacing HFC-152a with HCs in this scenario, 0.018 $MtCO_2eq$ of the high-GWP gas that would have been emitted by this facility during the lifetime of the one-component foam produced in a given year is eliminated (288,000 lb × 0.4536 kg/lb × 1 Mt/1,000,000,000 kg × 140 = 0.018 $MtCO_2eq$).

XPS Boardstock Foams

Table H-6: Base Case Assumptions for a Hypothetical Facility Using HFC-134a and CO_2-Based Blowing Agents

Variable	Value	Source
HFC-based Blowing Agent	HFC-134a and CO_2-based blends (90/10)	Assumption
Baseline Boardstock Foam Production per Line	100,000,000 bd-ft/yr (8,333,333 ft^3/yr)	Assumption (calculation)
Baseline Number of Operating Lines	10	Assumption
Density of Blowing Agent in Foam	0.2 lb/ft^3	Assumption
Baseline Polystyrene Consumption	2.0 lb/ft^3	Assumption
Price of HFC-134a	$2.45/lb[a]	Diversified CPC, 2006 and expert opinion
Price of CO_2	$0.19/lb	Airproducts, 2003
Price of Polystyrene	$0.67/lb	*Plastic News*, 2004
Direct Labor, Allocated Labor, Energy, and Allocated Costs	$0.03/bd-ft	Industry expert, 2005
Selling Price	$0.27/bd-ft	Industry expert, 2005
Baseline Operating Margin (profit)	20% of selling price (or about $0.05/bd-ft)	Industry expert, 2005

[a] For the purpose of this analysis, the cost of HFC-134a used in foams is assumed to equal the cost of HFC-134a bought in bulk, which ranges from $3.30 to $3.60 per pound as provided by Diversified CPC (2006). However, based on the historical as well as anticipated fluctuations in HFC-134a global pricing, this analysis assumes an approximate cost of $2.45 per pound. Note that this price is lower than that seen when buying smaller quantities, e.g., for servicing refrigeration and air conditioning systems. Historically, global capacity of HFC-134a was underused for several years, yielding depressed global pricing for HFC-134a. In 2003, strong global demand drove the market price of HFC-134a to $3.50 per pound. This price is expected to stay stable until at least 2007, when, as a result of potential new Asian capacity and reduced European consumption resulting from a ban on its use in mobile air conditioners in Europe beginning in 2011, the price is estimated to drop to about $2.75 per pound ($2.45 in 2000 dollars).

Table H-7: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-134a and CO_2-Based Blends with CO_2/Alcohol in XPS Boardstock Foam

Variable	Value	Source
Costs		
Capital costs	$5,013,674	Dow and OC, 2004
Price of alcohol	$0.68	Purchasing.com
Incremental increase in alternative direct costs	10% or $0.0027	Assumption
Rate Loss when Using Alternative Blowing Agent	10%	Assumption
Alternative Boardstock Foam Production per Line	90,000,000 bd-ft	Calculation
Alternative Polystyrene Consumption	2.2 lb/ft^3	Assumption
Alternative Blowing Agent	CO_2/ethanol (70/30)	Assumption
Blowing agent substitution ratio	2.16	Calculation
Number of Lines Converted to Alternative Blowing Agent	1	Assumption
Density of Alternative Blowing Agent in Foam	0.2 lb/ft^3	Assumption
Increase in Foam Density	10%	Dow and OC, 2004

Cost and Emissions Reduction Analysis for XPS Boardstock Foams

- **One-Time Costs.** Blends of CO_2 with alcohol (e.g., ethanol) require equipment operating at higher pressure than with HFC-134a. In addition, more highly corrosive by-products formed by using the alternative blowing agent result in safety and incineration considerations that require additional expenditures. According to industry experts, the one-time costs for replacing HFC-134a and CO_2-based blend with a CO_2 and alcohol blend are estimated to be about $5,013,674 million (approximately $1,823,154 million for increased pressure, $2,278,943 million for safety, and $911,577 million for incineration).
- **Annual Costs.** This analysis calculates a total increase in annual operating costs of $774,711 per year due to a loss in profit associated with this abatement option. The following annual costs are considered:
  - **Direct costs.** Annual direct costs per board-foot produced—including those associated with direct labor, allocated labor, energy, and allocated costs (e.g., accounting, legal, human resources)—are assumed to increase because the line that converts to LCD/alcohol produces less board-feet of foam. In the base case scenario, annual direct costs are estimated to be $0.027 per board-feet, whereas the alternative has an incremental annual cost of 10 percent or $0.0027 per board-feet from the lost capacity, because fixed costs will be spread over a 10 percent lower production volume.
  - **Loss of profit (for capacity loss).** This analysis estimates that the selling price of foam is $0.27 per board-feet, and that the operating margin with HFCs is 20 percent of the cost or about $0.05 per board-feet. When converting from HFC-134a and CO_2-based blends, there is an estimated rate loss of 10 percent. This rate loss equates to the loss of production of 10 million board-feet per year of foam from the one line converted, and hence a loss of $0.0027 per board-feet in profit.
  - **Calculation of annual costs.** Based on the assumption that the manufacturer would lose the sales of 10 million board-feet at an estimated selling price of $0.27 per board-feet, and that the operating margin is reduced and thus the company will be selling the remaining 90 million

board-feet at a lower profit margin (lower by \$0.0027 per board-feet), the annual costs are \$774,771 (i.e., 100,000,000 bd-ft × \$0.053/bd-ft – 90,000,000 bd-ft × [\$0.053/bd-ft – \$0.0027/bd-ft] = \$774,771).

- **Cost Savings.** Two types of cost savings are associated with this option: (1) cost savings associated with the alternative blowing agent used, and (2) cost savings associated with the amount of polystyrene resin used. These add to annual savings of \$3,582,474.
  - **Alternative blowing agent.** Because the alternative blowing agent is less expensive on a per-pound basis than HFC-134a, a \$3,471,165 annual cost savings is assumed to be associated with this option. This number is derived by subtracting the cost of the alternative blowing agent blend (a 70/30 blend of CO_2/ethanol yields a cost of 0.7 × \$0.19/lb + 0.30 × \$0.68/lb = \$0.337/lb) from the cost of the baseline blowing agent blend (a 90/10 blend of HFC-134a/CO_2 yields a cost of 0.9 × \$2.45/lb + 0.1 × \$0.19/lb = \$2.224/lb). For the base case, the cost is \$3,704,379 per year [8,333,333 ft3/yr (i.e., 100,000,000 bd-ft/yr) × 0.2 lb/ft3 × \$2.224/lb = \$3,704,379/yr]; for the alternative case, the cost is \$233,213/yr [7,500,000 ft3/yr (i.e., 90,000,000 bd-ft/yr) × 0.2 lb/ft3 × \$0.337/lb / 2.16 = \$\$233,213/yr]. Thus, the annual savings is \$3, 471,165. The blowing agent substitution ratio is assumed to be the molecular weight of the 90/10 HFC-134a/CO_2 blend divided by the molecular weight of the 70/30 CO_2/ehanol blend [(0.9 × 102 + 0.1 × 44)/(0.7 × 44 + 0.3 × 46) = 2.16].
  - **Polystyrene costs.** Base case polystyrene costs for one line are calculated by multiplying the total amount of foam produced in that line in the baseline scenario by the amount of polystyrene needed and the per-pound price of polystyrene (8,333,333 ft^3/yr × 2.0 lb/ft^3 × \$0.668/lb = \$11,130,899). Costs associated with the alternative are calculated by multiplying the total amount of foam that will be produced in the converted line by the amount of polystyrene needed (accounting for the 10 percent foam density increase) and the per-pound price of polystyrene (7,500,000 ft^3/yr × 2.0 lb/ft^3 × 1.10 × \$0.668/lb = \$11,019,590). The change in costs is an annual savings of \$111,309.
- **Emissions Reductions.** This analysis estimates that by replacing HFC-134a and CO_2-based blends with CO_2/ethanol, 0.885 $MtCO_2eq$ of the high-GWP gas that would have been emitted during the lifetime of the foam generated in a given year is eliminated (8,333,333 ft3/yr × 0.2 lb /ft3 × 0.9 lb HFC-134a per lb of blowing agent × 0.4536kg/lb × 1 Mt /1,000,000,000 kg × 1,300 = 0.885 $MtCO_2eq$).

PU Spray Foams

Table H-8: Base Case Assumptions for a Hypothetical PU Spray Foam Contractor Using HFC-245fa/CO_2 (Water)

Variable	Value	Source
Blowing Agent Component of Foam	10%	Assumption
HFC-245fa/CO_2 Ratio	75/25	Cannon, 2001; NCFI, 2001
Blowing Agent Use	12,735 lb	Estimated from Caleb (2000)
Foam Produced	127,347 lb	Calculation
Original Foam Cost	\$0.924/lb	Calculation[a]
Price of Isocyanate	\$0.97/lb	Cannon, 2001
Isocyanate/CO_2 Ratio	6	Cannon, 2001
Price of HFC-245fa	\$3.74/lb	Honeywell, 2003

[a] Average of five data points based on confidential information obtained for this report.

PU Spray: Replacing HFC-245fa/CO_2 (Water) and HFC-365mfc/HFC-227ea with CO_2 (Water)

Table H-9: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-245fa/CO_2 (Water) with CO_2 (Water) in PU Spray Foam

Variable	Value	Source
Capital Costs	Negligible[a]	Caleb, 2000
Fire Testing Costs	\$4,000[b]/Contractor	Caleb, 2000
Fire Retardant		
Incremental increase in fire retardant use	1%	Assumption
Cost of fire retardant	\$1.89/lb	Exxon, 2004
Blowing Agent Component of Foam	60%	Stepan, 2001
Assumed Increase in Cost of Foam	\$0.10/lb	Assumption
Increased Density		
Alternative foam costs	\$1.024/lb	Calculation
Increase in foam density	30%[c]	Assumption

[a] Assumes that contractors that are using HFC-245fa/CO_2 (water) have equipment that can use CO_2 (water) with minimal modification.
[b] Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2000).
[c] Assumes that foam density increases from 2.5 pound per cubic feet to 3.25 pound per cubic feet.

Cost and Emissions Reduction Analysis for PU Spray: Replacing HFC-245fa/CO_2 (Water) and HFC-365mfc/HFC-227ea with CO_2 (Water)

- **One-Time Costs.** According to industry experts, contractors that are using HFC-245fa/CO_2 (water) can use the same equipment for CO_2 (water) with only minimal modification (Caleb, 2000). This analysis assumes that a one-time cost of \$4,000 is needed to convert to this alternative blowing agent. This cost is associated with fire testing, which is based on \$250,000 fire testing costs for new formulations, 20 systems houses, and approximately 1,250 PU spray foam contractors that equally share these costs (\$250,000 × 20/1,250 = \$4,000) (Caleb, 2000).
- **Annual Costs.** This analysis assumes a unit annual operating cost of \$54,264 for this abatement option. These costs result from fire retardant use, costs due to increased density of foam, and the increased foam costs (refer to Table H-8 and Table H-9 for detailed assumptions). Costs associated with fire retardant use are \$2,409 and they are calculated by multiplying the amount of foam produced (127,347 pounds) by the incremental percentage of fire retardant in the foam (1 percent) and fire retardant costs (\$1.89 per pound). Increased foam costs are \$12,735 and are calculated by multiplying the amount of foam produced by the increase in foam costs (\$0.10 per pound). Costs due to increased density total \$39,121 and are calculated by multiplying the amount of foam produced by alternative foam costs (\$1.024 per pound) and the increase in foam density (30 percent). The alternative foam cost is the original foam cost (an average of five data points based on confidential information obtained for this report) plus the assumed increase in foam cost.
- **Cost Savings.** Because the alternative blowing agent is less expensive per pound than HFC-245fa, there is a \$9,723.72 annual cost savings associated with this option. Cost of the baseline blowing agent is \$54,320, while the cost of alternative blowing agents is \$44,596. Baseline costs are calculated by multiplying the per-pound cost of the blowing agent by the total amount of blowing agent used as follows: total blowing agent used × percentage that is HFC-245fa × per-

pound cost of HFC-245fa + total blowing agent used × percentage that is CO_2 × isocyanate/CO_2 ratio × price of isocyanate ([12,734.7lb × 0.75 × $3.74/lb] + [12,734.7lb × 0.25 × 6 × $0.97/lb] = $54,320). The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent ($0.97), the amount of blowing agent used (12,734.7 pounds), the isocyanate/CO_2 ratio (6), and the blowing agent component of foam using CO_2 (water) (60 percent).

- **Emissions Reductions.** This analysis estimates that by replacing HFC-245fa/CO_2 (water) with CO_2 (water), 0.004 $MtCO_2eq$ (i.e., 12,735 pounds, or 5.78 metric tons, of blowing agent multiplied by 75 percent content HFC-245fa and the GWP of 950) of the high-GWP gas that would have been emitted by this hypothetical PU spray foam manufacturer during the lifetime of the foam produced in a given year is eliminated.

PU Spray: Replacing HFC-245fa/CO_2 (Water) and HFC-365mfc/HFC-227ea with HCs

Table H-10: Assumptions and Costs Used in the Cost Analysis to Substitute HFC-245fa/CO_2 (Water) with HCs in PU Spray Foam

Variable	Value	Source
Capital Costs	$9727.63[a]	Exxon, 2001
US Fire Testing Costs	$4,000[b]/Contractor	Caleb, 2000
Fire Retardant		
Cost of fire retardant	$1.89/lb	Exxon, 2004
Incremental increase in fire retardant use	3%	Assumption
Training		
Employee training costs	$6,253/yr[c]	SPFA, 2001
Assumed Increase in Cost of Foam	$0.10/lb	Assumption
Foam Cost		
Increase in foam density	20%[d]	Assumption
Alternative foam cost	$1.024/lb	Calculation
Blowing Agent Cost		
Price of isopentane	$0.23/lb[e]	Exxon, 2004
Price of cyclopentane	$0.73/lb[e]	Exxon, 2004
Blowing agent substitution ratio	90%	Exxon, 2001

[a] Assumes that technical issues can be resolved. EU and Japan costs are different (see text).
[b] Based on $250,000 per systems house, 20 systems houses, and approximately 1,250 PU spray foam contractors (Caleb, 2000; Industry communication).
[c] Assumes a cost of approximately $208 per employee per day, two crews of three employees (total of six employees), and 5 days of training.
[d] Assumes that foam density increases from 2.5 pound per cubic feet to 3.0 pound per cubic feet.
[e] HCs used as a blowing agent in foams are approximately an 80/20 blend of cyclopentane and isopentane.

Cost and Emissions Reduction Analysis for PU Spray: Replacing HFC-245fa/CO_2 (Water) and HFC-365mfc/HFC-227ea with HCs

- **One-Time Costs.** One-time costs are calculated to be $13,728. According to industry experts, in the United States the capital costs for replacing HFC-245fa/CO_2 (water) with HCs are estimated to be $9,727.63 (Exxon, 2001). Based on $250,000 fire testing costs for new formulations, fire testing for 20 systems houses, and approximately 1,250 spray foam contractors, one-time costs associated with fire testing in the United States are $4,000 per contractor ($250,000 × 20/1,250) (Caleb, 2000).

One-time costs in the EU are $21,251, while in Japan these costs are $31,536 (BRE, 2004; JUFMA, 2004). U.S. costs were applied for all other countries/regions.

- **Annual Costs.** This analysis assumes a unit annual operating cost increase for this abatement option of $39,560. These costs result from fire retardant use, costs from increased density of foam, and worker safety training costs associated with the use of HCs. Tables H-8 and H-10 summarize assumptions associated with this abatement option. Costs associated with fire retardant use are $7,226 and are calculated by multiplying the amount of foam produced (127,347 pounds) by the incremental percent of fire retardant in foam (3 percent) and the additional fire retardant costs ($1.89 per pound). Worker training costs are estimated to be $6,253 and are calculated by multiplying costs of training per day by the number of workers and the number of training days, as shown in the footnotes to Table H-10. Costs from increased density are estimated to be $26,081 and are calculated by multiplying the amount of foam produced by the per-pound foam costs ($1.024 per pound) and the increase in foam density (20 percent). The alternative foam cost is the original foam cost (an average of five data points based on confidential information obtained for this report) plus the assumed increase in foam cost.
- **Cost Savings.** Because the alternative blowing agent is less expensive per kilogram than HFC-245fa, there is a $47,060 per year cost savings associated with this option. Baseline costs are calculated as shown in the previous example. The calculation of alternative blowing agent cost includes per-pound costs of alternative blowing agent ([80% × $0.73/lb] + [20% × $0.23/lb] = $0.63/lb), the amount of blowing agent used (12,735 pounds), and the blowing agent substitution ratio (90 percent). Cost savings are calculated by subtracting baseline blowing agent costs ($54,320 per year) from the alternative blowing agent costs ($7,260 per year).
- **Emissions Reductions.** As with the previous example, this analysis estimates that by replacing HFC-245fa/CO_2 (water) with HCs in this scenario, 0.004 $MtCO_2eq$ of the high-GWP gas that would have been emitted by this hypothetical foam manufacturer during the lifetime of the foam produced in a given year are eliminated.

PU Appliance Foams: Replacement Options

Cost and Emissions Reduction Analysis for PU Appliance: Replacing HFC-134a with HCs

- **One-Time Costs.** According to industry experts, the one-time cost for replacing HFC-134a with HCs is $50,000,000, which includes the capital cost to convert.
- **Annual Costs.** This analysis assumes that cyclopentane variable costs will be comparable to HFC-134a variable costs; therefore, no increased annual unit operating costs are assumed to be associated with this abatement option. Costs considered include High Impact Polystyrene (HIPS) liner, acrylonitrile butadiene styrene (ABS) liner, foam density, and energy costs.
- **Cost Savings.** Because cyclopentane is less expensive on a per-pound basis than HFC-134a, a $1,506,160 annual cost savings is associated with this option. This result derives from incremental per-unit cost difference ($2.81 per unit) multiplied by the number of units a hypothetical factory manufactures (536,000 units).
- **Emissions Reductions.** This analysis estimates that by replacing HFC-134a with HCs in this scenario, 0.99 $MtCO_2eq$ of the high-GWP gas that would have been emitted by this facility during the lifetime of the appliance foam produced in a given year is eliminated (0.00076 Mt × 1,300 [GWP of HFC-134a] = 0.99 $MtCO_2eq$).

Cost and Emissions Reduction Analysis for PU Appliance: Replacing HFC-245fa and HFC-365mfc/HFC-227ea with HCs

- **One-Time Costs.** According to industry experts, the one-time cost for replacing HFC-245fa with HCs is $50,000,000, which includes the capitol costs to convert.
- **Annual Costs.** Because of costs associated with overcoming the energy gap between the foam blown with HFC and the foam blown with the alternative blowing agent, total annual costs for replacing HFC-245fa with HCs are estimated to be $11,202,400. Costs considered include HIPS liner, ABS liner, foam density, energy, and savings from the cost of the blowing agent used. Individual costs for each of these elements were provided from industry; however, because they are considered confidential, costs are presented in aggregate.
- **Cost Savings.** Cost savings due to the blowing agent replacement associated with this abatement option are included in the annual costs above.
- **Emissions Reductions.** This analysis estimates that by replacing HFC-245fa with HCs in this scenario, 0.73 $MtCO_2eq$ of the high-GWP gas that would have been emitted by a representative facility during the lifetime of the PU appliance foam produced in a given year is eliminated (0.00076 Mt × 950 [GWP of HFC-245fa] = 0.73 $MtCO_2eq$).

PU Appliance: End-of-Life Options

Table H-11: General Assumptions Applicable to Both End-of-Life Options

Variable	Value	Source
Refrigerators per truckload	77 refrigerators	JACO, 2004
Travel distance to disassembly location	100 miles	Assumption
Truck operating rate	$1.60/mile	JACO, 2004
Average quantity of foam per unit	22.87 lb	Whirlpool, 2004
Labor rate	$14.42/hour	JACO, 2004
Steel content of the unit	132.3 lb	Whirlpool, 2004
Recovery value of steel	$0.036/lb	JACO, 2004
Volume of trucks (53 feet long x 102 inches wide x 13.5 feet high)	6,082 ft^3	Systems Transportation Equipment, 2004
Packing efficiency	70%	Assumption
Density of foam	2 lb/ft^3	ICF, 2004
HFC-245fa content of PU foam	13%	Whirlpool, 2004
HFC-134a content of PU foam	7.5%	Whirlpool, 2004

General Cost Analysis Applicable to Both End-of-Life Options

- **Collection and Consolidation.** This analysis assumes that appliances are collected and consolidated over a 4-hour period into full truckloads for shipment to a central disassembly location. The cost for collection and consolidation of appliances is $0.75 per refrigerator (i.e., 4 hours × $14.42/hour/77 refrigerators). The collection and consolidation is roughly the same for both the automated and manual processes.
- **Transportation of Appliances to Disassembly Location.** Transportation costs to the disassembly location are $2.45 per unit. The analysis assumes the appliances are shipped a distance of 100 miles from the collection and consolidation location to a central disassembly location. The

operating cost of the truck is assumed to be $1.60 per truckload mile. Truck unloading is conducted by two people over a 1 hour period, and 77 refrigerators per truckload is assumed. The labor rate is $14.42per hour (ICF Estimate; JACO, 2004). The calculation is as follows: ([$1.60 × 100] + [2 × $14.42])/77 = $2.45/refrigerator. Transportation of appliances to disassembly location costs are generally the same for both the automated and manual processes.

- **Disassembly of Appliances.** The appliances are then disassembled using the manual or automated process. See details below.
- **Recovery of HFC.** In the automated process with foam landfilling, the foam is ground and the HFC is recovered. See details below.
- **Recovery of Metals.** The steel content of the refrigerator is 132.3 pounds and steel prices are around $0.036 per pound. Benefits from salvaged steel are therefore $4.82 per unit. The benefits of other recovered materials (other than the HFC) are not included in this analysis.
- **Transportation of Foam to Disposal Location.** The cost to transport and landfill the ground PU foam (automated process) is assumed to be the same as the cost to transport and incinerate the unground PU foam (manual process). This analysis assumes that truckloads of ground or unground PU foam are shipped a distance of 100 miles from the disassembly/grinding location to an incineration/landfill location. The operating cost of the truck is assumed to be $1.60 per truckload mile (ICF estimate). The total weight of foam in the truck is the volume of that truck (6,082 cubic feet) multiplied by the packing efficiency (70 percent) and the density of the foam (2 pounds per cubic foot), which is roughly 8,514 pounds. The cost to transport the PU foam to the disposal location is equal to $0.43 per refrigerator (i.e., 100 m × $1.60 per mile /8,514 lb foam × 22.87 lb foam/refrigerator).
- **Disposal of Foam.** In the automated process, the ground foam is landfilled. In the manual process, the foam pieces are incinerated. See details below.
- **Emissions Reductions.** The HFC-134a blowing agent content at manufacture is 1.72 pounds, determined by multiplying 22.87 pounds of foam by 7.5 percent HFC-134a content. Likewise, 2.97 pounds of HFC-245fa are contained in each refrigerator at manufacture, determined by multiplying 22.87 pounds of foam by 13 percent HFC-245fa content. Because only 91 percent of the blowing agent remains at disposal, the maximum abatable emissions are 1.56 pounds (0.71 kg) of HFC-134a or 2.71 pounds (1.23 kg) of HFC-245fa, which translates to 0.92 tCO_2eq and 1.17 tCO_2eq, respectively. This analysis assumes that half of the refrigerators that are processed will contain HFC-134a foam, and the remainder will contain HFC-245fa foam. Thus, the maximum abatable emissions per refrigerator at disposal are 1.04 tCO_2eq. Thirty percent of what remains at disposal is emitted the year of disposal, in absence of any abatement, which translates to 0.313 tCO_2eq/unit. Additionally, 2 percent of the original charge would be emitted annually after disposal in the absence of abatement, or 0.023 tCO_2eq per unit per year (with slightly less in the final year) until all the charge was emitted. There may be additional indirect emissions reductions associated with this option, e.g., if the appliance is replaced with one that is more energy-efficient. These indirect emissions savings are not included in this analysis.

PU Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling

Table H-12: Assumptions Applicable to the Automated Process with Foam Landfilling

Variable	Value	Source
Refrigerators disassembled per hour	20	Mason, 2004
Grinding/absorption labor hours	4 hours/truckload	Assumption
Grinding/absorption equipment operating hours	4 hours/truckload	Assumption
Grinding/absorption equipment cost	$239.82 /hour	Mason, 2004
Percentage blowing agent recovered	90%	UNEP, 2002b; JACO, 2004
Recovery value of HFC-134a	$2.45/lb[a]	Diversified CPC, 2006 and expert opinion
Recovery value of HFC-245fa	$3.74/lb	Honeywell, 2003
Cost per container to landfill	$227.89/container	JACO, 2004
Landfill Container volume	540 ft^3	JACO, 2004
Capital cost for automated facility	$3,646,308	JACO, 2004
Capacity of automated facility	99,881 units/year	Calculation[b]

[a] For the purpose of this analysis, the cost of HFC-134a used in foams is assumed to equal the cost of HFC-134a bought in bulk, which ranges from $3.30 to $3.60 per pound as provided by Diversified CPC (2006). However, based on the historical as well as anticipated fluctuations in HFC-134a global pricing, this analysis assumes an approximate cost of $2.45 per pound. Note that this price is lower than that seen when buying smaller quantities, e.g., for servicing refrigeration and air conditioning systems. Historically, global capacity of HFC-134a was underused for several years, yielding depressed global pricing for HFC-134a. In 2003, strong global demand drove the market price of HFC-134a to $3.50 per pound. This price is expected to stay stable until at least 2007, when, as a result of potential new Asian capacity and reduced European consumption resulting from a ban on its use in mobile air conditioners in Europe beginning in 2011, the price is estimated to drop to about $2.75 per pound ($2.45 in 2000 dollars).

[b] Scaled on data that indicates a European plant processes 60 units per hour, each unit weighing 82 pounds, and that U.S. refrigerators weigh 245.9 lb (Mason, 2004; Whirlpool, 2004). The plant is assumed to operate 16 hours/day, 6 days/week, and 52 weeks/year.

- **Disassembly of Appliances.** For the automated process, this analysis assumes 3.85 labor hours are needed to disassemble a full truckload of 77 refrigerators The refrigerators are assumed to be disassembled at a rate of 20 refrigerators per hour (77/20 = 3.85). Total disassembly costs are $0.72 per refrigerator (i.e. [3.85 hr × $14.42/hr]/77 refrigerators = $0.72/ refrigerator).
- **Automated Grinding of Foam for Landfilling and Adsorption of HFC.** In the automated process, the PU foam is ground, the HFC is adsorbed onto a carbon substrate, and the ground PU waste is transported to the landfill. The non-labor operating cost of the grinding/adsorption equipment (e.g., electricity to operate the plant, periodic maintenance of the plant, etc.) is assumed to be $239.82 per hour (Mason, 2004). By grinding the foam, only an estimated 90 percent of the HFC is recovered, while the remaining 10 percent is lost to the atmosphere (UNEP, 2002b). Therefore, a total of 148 pounds of HFC is recovered per truckload (i.e., 164 pounds of HFC prior to processing/truckload × 90% of original HFC content remaining in foam at disposal). The amount of HFC per truckload prior to processing is calculated by multiplying the amount of HFC in refrigerator foam prior to disposal (assuming 50 percent of the units have HFC-245fa foam and 50 percent of the units have HFC-134a foam) by the total number of refrigerators per truckload. The calculation is as follows: 50% × (2.71 lb HFC-245fa/refrigerator + 1.56 lb HFC-134a/refrigerator) × 77 refrigerators = 164 lb/truckload). The content-weighted recovery value of the HFC is $3.10 per pound (i.e., 50% × [$3.74/lb + $2.45/lb]).

  However, there is a cost to recover the HFC, calculated to be $6.88 per pound. The cost of HFC recovery is calculated by dividing the grinding and adsorption costs by the total amount of HFC actually recovered ($1,017/truckload / 148 lb/truckload = $6.88/lb). Grinding and adsorption costs are calculated by summing the grinding and adsorption labor cost (4 hours/truckload × $14.42/hr = $58/truckload) and the cost of equipment used in grinding and adsorption ($239.82 /hr × 4 hr of equipment/truckload = $959/truckload).

The net recovery value of the HFC is therefore –$3.78 per pound (i.e., $3.10 – $6.88), or –$559.44 per truckload (i.e., –$3.78/lb × 148 lb/truckload), or –$7.27 per unit (i.e., –$559.44/ 77). Thus, grand total costs that include disassembly, processing, and recovery of the HFC are equal to $7.99 per unit (i.e., costs are $0.72 – [–$7.27]).

- **Landfilling of Foam.** This analysis assumes that landfilling of the PU foam occurs in a municipal solid waste landfill at a cost of $227.89 per pull[2] of foam for a 20 cubic yard cylinder. Assuming the container volume is 540 cubic feet (i.e., 20 cubic yards), the packing efficiency is 70 percent, and the density of foam is 2 pound per cubic foot, the weight of foam loaded is 756 pounds per container. Thus, landfilling foam will cost $0.30 per pound. The total cost of landfilling per unit is estimated to be $6.89 per refrigerator, calculated by multiplying the cost of landfilling per pound of foam with the foam content of the refrigerator (22.87 pounds of foam per unit).

Table H-13: Automated Process with Foam Landfilling

Method	Cost per Unit ($)
Collection/consolidation	$0.75
Transportation to disassembly location	$2.45
Disassembly & processing of refrigerators	$7.99 (includes savings from HFC recovery)
Transportation to disposal location	$0.43
Landfilling	$6.89
Total costs	**$18.50**
Savings (Salvaged Steel)	$4.82
Net Costs	**$13.68**

Cost and Emissions Reduction Analysis for the Automated Process with Foam Landfilling

- **One-Time Costs.** This analysis assumes a one-time capital cost of $3,646,308 for an Adelmann or MeWa plant (JACO, 2004).
- **Annual Costs.** The capacity of the facility is 99,881 refrigerators per year (JACO, 2004); therefore, the annual costs for this technology are $1,366,350, calculated by multiplying the capacity of the facility by the net costs of this technology per unit (Table H-13).
- **Cost Savings.** The savings from salvaging the steel and HFC blowing agent are accounted for in the annual costs above and in Table H-13.
- **Emissions Reductions.** This analysis estimates that by treating the appliance foam at the end of life with foam grinding, HFC adsorption, and landfilling, 0.03 $MtCO_2eq$ of emissions would be avoided the first year. Emissions reduction is calculated by summing the disposal emissions and emissions during the first year after disposal, and multiplying that sum by the capacity of the facility and the reduction efficiency. Therefore, emissions reduction equals (0.313 tCO_2eq/unit + 0.023 tCO_2eq/unit) × 99,881 units × 90%. Additionally, as presented above, 0.023 tCO_2eq of emissions per unit would be reduced each year that the foam spends in the landfill. For the automated process, assuming a reduction efficiency of 90%, this equates to 0.002 $MtCO_2eq$ per year.

[2] A batch quantity of foam that would fill 1 container.

PU Appliance: Manual Process with Foam Incineration

Table H-14: Assumptions Applicable to the Manual Process with Foam Incineration

Variable	Value	Source
Loading labor hours	4 hours	JACO, 2004
Unload labor hours	2 hours	JACO, 2004
Cost of disassembly	$31.91/unit	JACO, 2004
Cost to incinerate foam	$0.48/lb	JACO, 2004
Percentage foam recovered	92.5%	JACO, 2004
Percentage blowing agent incinerated	98%	UNEP, 2002b
Capital cost to initiate operation	$182,315	JACO, 2004
Capacity of manual operation	10,000 units/year	JACO, 2004

- **Manual Dismantling of Foam for Incineration.** For the manual process, this analysis assumes that 90 to 95 percent of the foam is recovered (for calculation purposes, 92.5 percent is used). In the manual process, the large foam pieces are separated and sent for incineration. The costs of disassembly are assumed to be $31.91 per refrigerator (JACO, 2004).
- **Incineration of Foam.** The cost of incineration of PU foam is estimated to be $10.12 per refrigerator. This cost is derived by multiplying the foam content of the refrigerator (22.87 pounds) prior to processing by the percent of foam recovered (92.5 percent) and by the cost of incineration per pound ($0.48 per pound).

Table H-15: Manual Process with Foam Incineration

Method	Cost per Unit ($)
Collection/consolidation	$0.75
Transportation to disassembly location	$2.45
Disassembly & processing of refrigerators	$31.91
Transportation to disposal location	$0.43
Incineration	$10.12
Total Costs	**$45.65**
Savings (Salvaged Steel)	$4.82
Net Costs	**$40.83**

Cost and Emissions Reduction Analysis for the Manual Process with Foam Incineration

- **One-Time Costs.** This analysis assumes a one-time capital cost of $182,315 (JACO, 2004) for establishing offices, renting equipment, leasing land for collection, etc.
- **Annual Costs.** The capacity of the facility is 10,000 refrigerators per year (JACO, 2004); therefore, the annual costs for this technology are $408,289, calculated by multiplying the capacity of the facility with the net costs of this technology per unit. Table H-15 summarizes costs associated with this specific technique.
- **Cost Savings.** The savings from salvaged steel ($4.82 per unit) are accounted for above.

- **Emissions Reductions.** This analysis estimates that by treating the appliance foam at the end of life with incineration, 0.003 $MtCO_2eq$ of the high-GWP gas can potentially be eliminated annually. Accounting for the assumption that 92.5 percent of the foam can be recovered from the appliance, and that incineration destroys 98 percent of the HFC in that foam (an overall reduction efficiency of 90.6 percent) (JACO, 2004), abated emissions are calculated by multiplying disposal emissions and leak emissions of the first year after disposal by capacity of facility and reduction efficiency, ([0.313 tCO_2eq/unit + 0.023 tCO_2eq/unit] × 10,000 units × 90.6%). Additionally, 0.023 tCO_2eq of emissions per unit would be reduced each year that the foam spends in the landfill. For the manual process, assuming a reduction efficiency of 90.6%, this equates to 0.0002 $MtCO_2eq$ per year.

H.1 Abatement Option Summary Tables

Table H-16: Foams Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
XPS Boardstock: HFC-134a/CO_2 (LCD)-based blends to CO_2 (LCD)/Alcohol	–$7.87	–$7.87	1.50	9.8%	1.50	9.8%
PU Spray: HFC-245fa/CO_2 (water) to HC	–$5.19	–$2.91	0.25	1.6%	1.75	11.4%
PU One Component HFC-152a to HC	–$2.12	–$2.12	0.04	0.3%	1.79	11.6%
PU One Component HFC-134a to HC	–$1.76	–$1.76	0.29	1.9%	2.08	13.5%
PU Continuous and Discontinuous: HFC-134a to HC	$0.86	$0.86	0.35	2.3%	2.43	15.8%
PU Appliance: Automated Process with Foam Grinding, HFC Adsorption, and Foam Landfilling	$36.07	$36.07	0.00	0.0%	2.43	15.8%
PU Spray: HFC-245fa/CO_2 (water) to CO_2 (water)	$41.84	$41.84	0.22	1.5%	2.66	17.3%
PU Appliance: HFC-134a to HC	$42.06	$42.06	0.03	0.2%	2.69	17.5%
PU Appliance: Manual Process with Foam Incineration	$82.54	$82.54	0.00	0.0%	2.69	17.5%
PU Appliance: HFC-245fa to HC	$192.54	$192.54	0.74	4.8%	3.43	22.3%

Table H-17: Foams Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
	Low	High				
XPS Boardstock: HFC-134a/CO_2 (LCD)-based blends to CO_2 (LCD)/Alcohol	–$7.87	–$7.87	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-152a to HC	–$2.12	–$2.12	0.06	0.2%	4.14	14.5%
PU One Component HFC-134a to HC	–$1.76	–$1.76	0.48	1.7%	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%

Appendix I: Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Aerosols

Cost and Emissions Reduction Analysis for MDI: Replacement with DPIs

Cost assumptions for this option were taken directly from Ecofys (2000).[1] The following describes the cost and emissions inputs used to derive the final dollars per ton of carbon dioxide equivalent (tCO_2eq) for the DPI option, the results of which are presented in Section IV.5.4.

- **One-Time Costs.** No one-time costs are assumed for implementing DPIs.
- **Annual Costs.** The annual cost associated with using DPIs was estimated to be approximately $571,400 per metric ton of substance. This cost was based on €533,000 (in 1999 Euros) per metric ton of substance (Enviros March, 2000), which translates to an annual cost of $552,544 using the 1999 exchange rate of $0.964629 Euros to 1 US dollar (X-rates.com, 2006).[2] According to the source cited by Ecofys (2000), this annual cost incurred by the industry takes into account the increase in cost of DPI treatment, the cost to market the new treatment, and the cost to retrain the patients in using the DPI (Enviros March, 2000).
- **Cost Savings.** No cost savings are assumed for this option.
- **Emissions Reductions.** This option is assumed to avoid 1,000 kilograms of HFC emissions under the cost scenario as provided by Ecofys (2000). This reduction equates to 1,300 metric tons of carbon dioxide equivalent (tCO_2eq), calculated using the GWP of HFC-134a (i.e., 1 metric ton of HFC-134a multiplied by the GWP of 1,300 and the reduction efficiency of 100 percent).

Cost and Emissions Reduction Analysis for Non-MDI: Replacement with Lower GWP HFCs

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for converting to a lower GWP aerosol propellant, the results of which are presented in Section IV.5.4.

- **One-Time Costs.** Costs of converting a filling facility to accept HFC-152a may range from $400,000 to $500,000 (Dupont, 2000). To be conservative, this analysis assumes that a one-time cost of $500,000 is required to achieve the assumed reduction scenario for a facility producing 10 million cans requiring two ounces of propellant each on an annual basis.
- **Annual Costs.** The operation and maintenance costs are assumed not to vary based on the use of the alternative propellant; therefore, the increase in annual costs is zero. Any potential insurance cost increase associated with using HFC-152a is not factored into the cost analysis.

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[1] The Ecofys (2000) report cites Enviros March (2000) costs, which were developed assuming a conversion to DPIs from an MDI containing HFC-134a (Enviros March, 2000). For this analysis, these costs and the associated emissions reductions were applied to the total baseline MDI market, which consists of MDIs that use HFC-134a and HFC-227ea.

[2] The 1999 conversion rate is used because the cost cited in Enviros March is in 1999 Euros; the annual cost was then converted to 2000 USD.

- **Cost Savings.** This analysis assumes the cost per pound of HFC-134a is approximately $2.45 per pound,[3] slightly higher than the cost per pound of HFC-152a ($1.58 per pound) (Diversified CPC, Inc. 2006). Thus, filling a can that requires 2 ounces of propellant with HFC-134a costs $0.34, versus $0.24 with HFC-152a; therefore, the difference in chemical costs is a savings of $0.10 per can. A costs savings of approximately $0.10 per can translates into a cost savings of $1,090,257, assuming that a filling facility is producing 10 million cans per year.
- **Emissions Reductions.** Assuming that 10 million cans are converted from HFC-134a to HFC-152a, and the typical quantity of propellant required per unit is two ounces (or 0.0567 kilograms), the potential quantity of HFC-134a avoided by the facility in one year is estimated to be 567,000 kilograms. Accounting for the reduction efficiency of 89.2 percent, this facility could avoid 0.66 $MtCO_2eq$ per year (i.e., 567 metric tons of HFC-134a multiplied by the GWP of 1300 and the reduction efficiency of 0.892.

Cost and Emissions Reduction Analysis for Non-MDI: Replacement with NIK Alternatives

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for NIK replacements, the results of which are presented in Section IV.5.4.

- **One-Time Costs.** Significant variability exists in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This variability is attributable to the wide range of potential aerosol and NIK product types. For this analysis, an incremental capital cost of $250,000 per facility producing an annual total of 10 million cans requiring two ounces of propellant each was used (USEPA, 2001).
- **Annual Costs.** In the case of liquid pumps and solid applicators, capital investments are generally lower, but material costs will be higher than for HFCs (UNEP, 1999). To account for higher material costs of the particular sticks, rollers, and pumps being used, the analysis assumes an estimated $500,000 in annual costs for a facility that produces 10 million units (e.g., cans, pumps) (USEPA, 2001).
- **Cost Savings.** Despite the costs of this option, overall savings can be significant, primarily because of the avoidance of HFC costs. Filling a can that requires two ounces of propellant with an HFC was estimated to cost approximately $0.23 (based on the average price per pound of HFC-134a and HFC-152a weighted by the mass percentage of the U.S. baseline emissions comprised by each gas) versus no costs of chemical for an NIK-formulated can, resulting in a savings of $2,343,458 per year for a filling facility that produces 10 million total cans in 1 year.
- **Emissions Reductions.** Assuming that 10 million units are converted from an HFC to an NIK process, each unit using approximately 2 ounces of propellant, the quantity of HFC avoided in 1 year was estimated at 567,000 kilograms, or 0.31 $MtCO_2eq$ using the weighted average GWP of 538.

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[3] The cost of HFC-134a in 40,000 pound containers (tankers) ranges from $3.30 to $3.60 per pound (Diversified CPC, 2006). However, based on the historical as well as anticipated fluctuations in HFC-134a global pricing, this analysis assumes an approximate cost of $2.45 per pound. Note that this price is lower than that seen when buying smaller quantities, e.g., for servicing refrigeration and air conditioning systems. Historically, global capacity of HFC-134a was underused for several years, yielding depressed global pricing for HFC-134a at approximately $1.50 to $1.60 per pound lower than the cost of HFC-152a. In 2003, strong global demand drove the market price of HFC-134a to $3.50 per pound. This price is expected to stay stable until at least 2007, when, as a result of potential new Asian capacity and reduced European consumption resulting from a ban on its use in mobile air conditioners in Europe beginning in 2011, the price is estimated to drop to about $2.75 per pound ($2.45 in 2000 dollars).

Cost and Emissions Reduction Analysis for Non-MDI: Replacement with Hydrocarbon Aerosol Propellants

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for converting to an HC aerosol propellant, the results of which are presented in Section IV.5.4.

- **One-Time Costs.** The one-time cost of converting a filling facility to accept HC propellants can range from $10,000 to $1.2 million, including the costs of installing safety control features (Nardini, 2002). The high conversion cost accounts for the fact that HCs are highly flammable gases that require stringent safety precautions in manufacturing, storage, handling, transport, and customer use. The range in one-time cost varies based on the need for investments in new equipment and the need to relocate to regions where the use of HCs is considered safe (Nardini, 2002). One-time costs are expected to be lower, for instance, for a facility converting from HFC-152a to an HC propellant where flammability controls are likely to already be in place. This report assumes that a facility producing 10 million cans per year must invest $325,000 for this option.
- **Annual Costs.** Annual costs may be incurred to ensure good handling practices of HCs that are considered hazardous air pollutants (HAPs). These practices include regular maintenance on fire prevention devices such as fire detection systems, sprinklers, and shut-off valves; and proper safety training for employees (UNEP, 2002). Such costs have not been quantified for this analysis; however, future work may be performed to investigate estimated annual costs.
- **Cost Savings.** HC prices are generally lower than those of HFCs, which lowers overall production costs and contributes to cost savings. To represent savings for this option, filling a can that requires 2 ounces of an HFC propellant was estimated to cost $0.23 (based on the average price per pound of HFC-134a and HFC-152a weighted by the mass percentage of the U.S. baseline emissions comprised by each gas) versus $0.027 for the cost of an HC (based on the price of a propane/isobutane blend of $0.27 per pound [Diversified CPC, 2004]), which yields a cost savings of approximately $2,001,456 per year experienced by a filling facility that produces 10 million cans in 1 year.
- **Emissions Reductions.** As with the scenario used for the NIK option, the quantity of HFC avoided in 1 year by transitioning to HCs was estimated at 567,000 kilograms, or 0.31 $MtCO_2eq$.

I.1 Abatement Option Summary Tables

Table I-1: Aerosols Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
DPI	$439.54	$439.54	0.55	5.0%	0.55	5.0%
HFC to HC	–$6.34	–$6.34	3.27	10.0%	3.27	10.0%
HFC to NIK	–$5.87	–$5.87	3.27	10.0%	6.54	20.0%
HFC-134a to 152a	–$1.07	–$1.07	6.06	18.5%	12.60	38.5%

Table I-2: Aerosols Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO_2eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO_2eq)	Cum. % Reduction from 2020 Baseline
	Low	High				
DPI	$439.54	$439.54	10.06	50.0%	10.06	50.0%
HFC to HC	–$6.34	–$6.34	3.95	10.0%	3.95	10.0%
HFC to NIK	–$5.87	–$5.87	3.95	10.0%	7.91	20.0%
HFC-134a to 152a	–$1.07	–$1.07	14.64	37.0%	22.54	57.0%

Appendix J: Cost and Emissions Reduction Analysis for Options to Abate International HFC Emissions from Fire Extinguishing

Cost and Emissions Reduction Analysis for Inert Gas Systems

Various data and assumptions about the costs and emissions reductions associated with inert gas were used to analyze this option. U.S. costs were determined relative to conventional HFC-227ea systems, which dominate the HFC flooding market in the United States. This analysis scales the costs of inert gas systems in other countries to U.S. costs based on confidential country-specific cost information obtained for this report from HTOC members, as described in more detail below. The following describes the cost and emissions inputs used to derive the final dollars per ton of carbon dioxide equivalent (tCO_2eq) for this option, the results of which are presented in Section IV.6.4.

- **One-Time Costs.** This analysis bases average capital costs for inert gases on average selling prices to distributors/installers, as provided in Wickham (2003b), which provides a comprehensive cost comparison of total flooding systems.[1] Accordingly, in the United States, inert gas systems cost approximately $31.89 per cubic meter of protected space. This represents an increase of approximately $5.63 over conventional HFC-227ea systems, which are estimated to cost an average $26.25 per cubic meter of protected space (average across all space sizes). In addition, because inert gas systems require more space to house gas cylinders than conventional HFC systems, in some cases there will be additional one-time costs to construct the additional space for storage. Specifically, an additional 0.023 square feet (0.0021 square meters) of floor space is needed per cubic meter of protected space (Wickham, 2003b).

  Assuming a construction cost of $150 per square foot (R.S. Means, 2001), this additional space requirement translates into an incremental one-time cost of $3.43 per cubic meter of protected space. The total incremental capital cost of this option in the United States is thus $9.07 per cubic meter of protected space (i.e., $5.63 + $3.43).

  In all developing countries, capital costs for this option were scaled based on cost estimates provided by HTOC members from developing countries. Specifically, incremental capital costs (relative to conventional HFC-227ea systems) were assumed to be 10 percent greater in non-Annex I (developing) countries than in the United States, and 10 percent less in Japan, based on an analysis of cost estimates provided by several HTOC members (Hughes Associates, 2001). In all other Annex I countries, capital costs were assumed to be the same as in the United States.

- **Annual Costs.** Depending on the application, the space required to house additional gas cylinders (an additional 0.023 square feet per cubic meter of protected space) will need to be heated and cooled. For completeness, the additional annual heating and cooling costs are considered in this analysis. Based on average U.S. electricity costs of $8 per square foot (R.S. Means, 2001), this option is associated with an annual cost of $0.18 per cubic meter of protected space in the United States. For all other countries, this annual cost was adjusted by average

[1] The cost estimates in Wickham (2003b) do not include agent distribution piping and fittings, pipe supports and hangers, actuation tubing and fittings, electrical cables, and junction boxes or labor to install. Although the costs identified in Wickham (2003b) for inert gas and HFC-227ea systems will be higher for end-users, the cost differential between these two systems is assumed to be relatively comparable.

country- or region-specific electricity prices (average of 1994–1999) based on Energy Information Administration (USEIA) (2000).

- **Cost Savings.** Annual savings result from the avoided HFC-227ea emissions and associated replacement costs, which would have been incurred had a conventional HFC system been used in place of inert gas (which, for this analysis, is assumed to have no agent cost). Because, on average, 0.633 kilogram of HFC-227ea is needed to protect 1 cubic meter of space (Wickham, 2003b), and assuming an annual emissions rate of 2 percent of the installed base, the emissions of approximately 12.7 grams of HFC-227ea is avoided each year per cubic meter of protected space. Based on an average HFC-227ea cost of $27.86 per kilogram (Wickham, 2003b), this translates into an annual savings of $0.35 per cubic meter of protected space (i.e., 12.7 grams × $27.86/kg).
- **Emissions Reductions.** As mentioned in the bullet above, under the inert gas systems described above, direct emissions of approximately 12.7 grams of HFC-227ea, or nearly 0.037 tCO_2eq, can be avoided per cubic meter of protected space. (0.0127 kg × 1 ton/1,000 kg × 2,900 [GWP of HFC-227ea] = 0.037 tCO_2eq).

  However, indirect emissions penalties are associated with this option, because of additional heating and cooling requirements. The indirect emissions penalty is approximately 0.002 tCO_2eq per cubic meter of protected space in the United States, assuming an additional 3.6 kilowatt-hours are required[2] and using an average emissions factor for electricity generation of 0.606 kilogram CO_2 per kilowatt-hour (USEIA, 2004). In all other countries, the indirect emissions penalty was calculated by multiplying the emissions penalty assumed for the United States (0.002 tCO_2eq) by a ratio of U.S. to regional national average CO_2 emissions rates for electricity production, based on IPCC (2005).

  Therefore, in the United States, the net annual emissions reduction associated with this option is approximately 0.034 tCO_2eq per cubic meter of protected space (i.e., 0.037 – 0.002).

Cost and Emissions Reduction Analysis for Water Mist Systems

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for the water mist option, the results of which are presented in Section IV.6.4.

- **One-Time Costs.** This analysis bases the average capital costs for water mist systems on the average selling prices to distributors for systems used in marine applications, as provided in Wickham (2003b), which provides a cost comparison of total flooding systems.[3] According to that report, capital costs of water mist systems used in marine systems to protect spaces of 3,000 m3 and larger are estimated to be $27.77 per cubic meter of protected space—or $3.81 more per cubic meter of protected space than conventional HFC-227ea systems in large spaces (which are estimated to cost an average of $23.96 per cubic meter of protected space in these sized spaces).[4] For nonmarine applications, costs are more competitive than those presented here, because the

[2] This estimate assumes an average U.S. electricity cost of $0.05 per kilowatt-hour (USEIA, 2005); given that annual heating/cooling costs are estimated to equal approximately an additional $0.18 per year, this implies an additional consumption of approximately 3.6 kilowatt-hours ($0.18/$0.05/kWh = 3.6 kWh).

[3] The cost estimates provided in Wickham (2003b) do not include feed water pipes, low pressure piping, electrical cables, and junction boxes or labor to install. Therefore, water mist and HFC-227ea systems costs will be higher than presented here, but the cost differential between these two systems is assumed to be comparable.

[4] The cost of conventional HFC-227ea systems is less per cubic meter of protected space in large spaces than in smaller ones.

requirements for land-based systems are not as stringent as those currently required by the IMO (Wickham, 2003a). This analysis uses the costs for marine rather than land-based systems to obtain conservative results (i.e., higher costs). Other costs presented below, however, are based on nonmarine applications because other data were not available.

In addition, because water mist systems require more space than conventional HFC systems, one-time costs associated with constructing additional space are also considered. Specifically, an additional 0.0472 square feet (0.0044 square meters) of floor space is needed per cubic meter of protected space (Wickham, 2003b). Assuming a construction cost of $150 per square foot in the United States (R.S. Means, 2001), this additional space requirement translates into an incremental one-time cost of $7.08 per cubic meter of protected space. Therefore, the total incremental capital cost of this option in the United States is estimated to be $10.89 per cubic meter of protected space (i.e., $3.81 + $7.08).

Reliable international cost information on water mist systems was only obtained for India and Russia. According to international experts, capital costs are the same in Russia as in the United States, and about 10 percent higher in India (Hughes Associates, 2001). India is used as a proxy for estimating costs in all other developing countries (i.e., costs are assumed to be 10 percent greater than those in the United States). In all other Annex I countries, the U.S. cost estimates are used as a proxy.

- **Annual Costs.** Because the additional space required to house water mist systems (0.0472 square feet per cubic meter of protected space) will need to be heated and cooled, annual heating and cooling costs for this additional space are considered in this analysis. Based on average U.S. electricity costs of $8 per square foot (R.S. Means, 2001), this option is associated with an annual cost of $0.38 per cubic meter of protected space in the United States. In all other countries, this annual cost is adjusted by average country- or region-specific electricity prices (average of 1994–1999) based on USEIA (2000).
- **Cost Savings.** Annual savings are associated with the avoided HFC-227ea emissions and associated replacement costs, which would have been incurred had a conventional HFC system been used in place of water (which for this analysis is assumed to have no agent cost). Because an average of 0.630 kilogram of HFC-227ea is needed to protect 1 cubic meter of space (for 3,000–5,000 m3 spaces) (Wickham, 2003b), and assuming an annual emissions rate of 2 percent of the installed base, it is assumed that the emissions of approximately 12.6 grams of HFC-227ea is avoided each year (i.e., 0.630 kilogram × 2 percent). Based on an average HFC-227ea cost of $27.86 per kilogram, this translates into an annual savings of $0.35 per cubic meter of protected space (Wickham, 2003b).
- **Emissions Reductions.** Under the water mist systems described above, the direct emissions of approximately 12.6 grams of HFC-227ea can be avoided, resulting in the reduction of approximately 0.037 tCO_2eq per cubic meter of protected space.

  However, indirect emissions penalties are associated with this option, because of additional heating and cooling requirements. The indirect emissions penalty is approximately 4.9 kilograms of carbon dioxide equivalent (or 0.0049 tCO_2eq) per cubic meter of protected space in the United States, assuming an additional 7.4 kilowatt-hour are required[5] and using an average emissions

[5] This estimate assumes an average U.S. electricity cost of $0.05 per kilowatt-hour (USEIA, 2005); given that annual heating/cooling costs are estimated to equal an additional $0.38 per year, this implies an additional consumption of approximately 7.4 kilowatt-hours.

factor for electricity generation of 0.606 kilogram CO_2 per kilowatt-hour (USEIA, 2004). In all other countries, the indirect emissions penalty was calculated by multiplying the emissions penalty assumed for the United States (4.9 kilograms of carbon dioxide equivalent) by a ratio of U.S. to regional national average CO_2 emissions rates for electricity production, based on IPCC (2005).

Therefore, in the United States, the net annual emissions reduction associated with this option is approximately 0.032 tCO_2eq per cubic meter of protected space (i.e., 0.037 – 0.0049 = 0.032).

Cost and Emissions Reduction Analysis for FK-5-1-12

The following describes the cost and emissions inputs used to derive the final dollars per tCO_2eq for FK-5-1-12 systems, the results of which are presented in Section IV.6.4.

- **One-Time Costs.** This analysis bases average capital costs for FK-5-1-12 systems on the average selling prices to distributors/installers, as provided in Wickham (2003b), which provides a cost comparison of total flooding systems.[6] According to this report, in the United States, capital costs of FK-5-1-12 systems are estimated to be $33.68 per cubic meter of protected space—or $7.43 more than conventional HFC systems (estimated to cost an average $26.25 per cubic meter of protected space [average across all space sizes]).[7] Also, while the floor space requirements for this option are very similar to those of HFC systems, there is a slight increase in the floor space needed to protect each cubic meter of space (approximately 0.0005 square feet). Assuming an average construction cost of $150 per square foot (R.S. Means, 2001), this translates into an incremental one-time construction cost of approximately $0.07 per cubic meter of protected space. Therefore, the total incremental one-time cost of this option is $7.50 per cubic meter of protected space (i.e., $7.43 + $0.07). Because of a lack of available data on the costs of this option in other countries, no regional cost adjustments were made to this capital cost.
- **Annual Costs.** Because the additional space requirement associated with this option relative to conventional HFC systems is so small (an average of 0.0005 square feet per cubic meter of protected space [Wickham, 2003b]), the additional annual costs associated with heating and cooling are also very small—less than $0.01 annually per cubic meter of protected space. This cost was derived by multiplying the additional space requirement (0.0005 square feet/cubic meter of protected space) by the average electricity cost to heat/cool space—which is assumed to be $8 per square foot (R.S. Means, 2001). In all other countries, this annual cost of $0.004 was adjusted by average country- or region-specific electricity prices (average of 1994–1999) based on USEIA (2000).

  In addition, an annual cost of $0.50 per cubic meter of protected space is assumed to be associated with annual emissions/agent replacement costs. This cost is based on the assumption that approximately 0.74 kilograms of FK-5-1-12 agent is required to protect every cubic meter of protected space, that 2 percent of this amount is leaked each year, and that FK-5-1-12 costs $33.70 per kilogram.

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[6] The cost estimates in Wickham (2003b) do not include agent distribution piping and fittings, pipe supports and hangers, actuation tubing and fittings, electrical cables, and junction boxes or labor to install. Although the costs identified in Wickham (2003) for FK-5-1-12 and HFC-227ea systems will be higher for end-users, the cost differential between these two systems is assumed to be relatively comparable.

[7] To be conservative, this analysis uses this figure, although others have reported increased costs of only around $3.28 per cubic meter of protected space (Werner, 2004b).

- **Cost Savings.** Annual savings are associated with the avoided HFC-227ea emissions and associated replacement costs, which would have been incurred had a conventional HFC system been used in place of FK-5-1-12. Because on average approximately 0.633 kilogram of HFC-227ea are needed to protect 1 cubic meter of space (Wickham, 2003b), and assuming an annual emissions rate of 2 percent of the installed base, it is assumed that the emissions of approximately 12.7 grams of HFC-227ea is avoided each year (i.e., 0.633 kilograms × 2 percent). Based on an average HFC-227ea cost of $27.86 per kilogram (Wickham, 2003b), this translates into an annual savings of $0.35 per cubic meter of protected space.
- **Emissions Reductions.** Under the FK-5-1-12 option described above, the direct emissions of approximately 12.7 grams of HFC-227ea can be avoided per cubic meter of protected space, resulting in a reduction of 0.037 tCO_2eq per cubic meter of protected space (given the GWP of HFC-227ea of 2,900).

  Slight indirect emissions penalties are associated with this option, because of additional heating and cooling requirements. The indirect emissions penalty is 0.05 kilogram of carbon dioxide equivalent per cubic meter of protected space in the United States, assuming an additional 0.08 kilowatt-hour are required[8] and using an average emissions factor for electricity generation of 0.606 kilogram CO_2 per kilowatt-hour (USEIA, 2004). In all other countries, the indirect emissions penalty was calculated by multiplying the emissions penalty assumed for the United States (0.05 kilogram of carbon dioxide equivalent) by a ratio of U.S. to regional national average CO_2 emissions rates for electricity production, based on IPCC (2005).

J.1 Abatement Option Summary Tables

Table J-1: Fire Extinguishing Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost ($2000\$/tCO_2eq$) DR=10%, TR=40%		Direct Emissions Reduction ($MtCO_2eq$)	Indirect Emissions Reduction ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
	Low	High					
FK-5-1-12	$37.26	$37.58	0.16	0.00	2.2%	0.16	2.2%
Inert Gases	$34.53	$48.85	0.20	-0.01	2.7%	0.36	4.8%
Water Mist	$48.16	$82.40	0.03	0.00	0.4%	0.39	5.2%

[8] This estimate assumes an average U.S. electricity cost of $0.05 per kilowatt-hour; given that annual heating/cooling costs are estimated to equal $0.004 per year, this implies an additional consumption of approximately 0.08 kilowatt-hour.

Table J-2: Fire Extinguishing Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Direct Emissions Reduction (MtCO_2eq)	Indirect Emissions Reduction (MtCO_2eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO_2eq)	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%

Appendix K: Cost and Emissions Reduction Analysis for Options in Aluminum Production

K.1 Abatement Option Summary Tables

Table K-1: Aluminum Production Abatement Option Summary for 2010 World, No-Action Baseline

Reduction Option	Cost(2000$/$tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
	Low	High				
Retrofit—Minor: SWPB	–$2.44	$0.73	1.61	2.3%	1.61	2.3%
Retrofit—Minor: VSS	–$5.75	$0.75	7.86	11.3%	9.48	13.6%
Retrofit—Minor: HSS	$0.71	$4.75	2.27	3.2%	11.74	16.8%
Retrofit—Major & Minor: SWPB	$3.97	$5.26	0.00	0.0%	11.74	16.8%
Retrofit—Minor: CWPB	–$16.93	$6.13	3.90	5.6%	15.64	22.4%
Retrofit—Major (marginal): SWPB	$6.27	$6.98	4.84	6.9%	20.48	29.3%
Retrofit—Major & Minor: CWPB	–$14.84	$8.00	0.00	0.0%	20.48	29.3%
Retrofit—Major & Minor: VSS	$7.10	$13.42	0.00	0.0%	20.48	29.3%
Retrofit—Major & Minor: HSS	$9.77	$13.73	0.00	0.0%	20.48	29.3%
Retrofit—Major (marginal): CWPB	–$9.35	$14.17	1.30	1.9%	21.77	31.2%
Retrofit—Major (marginal): HSS	$19.21	$23.25	2.27	3.2%	24.04	34.4%
Retrofit—Major (marginal): VSS	$20.37	$26.88	7.86	11.3%	31.90	45.7%

Table K-2: Aluminum Production Abatement Option Summary for 2010 World, Technology-Adoption Baseline

Reduction Option	Cost(2000$/$tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
	Low	High				
Retrofit—Minor: SWPB	–$2.44	$0.73	1.04	2.7%	1.04	2.7%
Retrofit—Minor: VSS	–$5.75	$0.75	0.20	0.5%	1.24	3.2%
Retrofit—Minor: HSS	$0.71	$4.75	0.63	1.6%	1.87	4.8%
Retrofit—Major & Minor: SWPB	$3.97	$5.26	0.00	0.0%	1.87	4.8%
Retrofit—Minor: CWPB	–$16.93	$6.13	0.23	0.6%	2.10	5.4%
Retrofit—Major (marginal): SWPB	$6.27	$6.98	3.13	8.0%	5.23	13.4%
Retrofit—Major & Minor: CWPB	–$14.84	$8.00	0.00	0.0%	5.23	13.4%
Retrofit—Major & Minor: VSS	$7.10	$13.42	0.00	0.0%	5.23	13.4%
Retrofit—Major & Minor: HSS	$9.77	$13.73	0.00	0.0%	5.23	13.4%
Retrofit—Major (marginal): CWPB	–$9.35	$14.17	0.08	0.2%	5.31	13.6%
Retrofit—Major (marginal): HSS	$19.21	$23.25	0.63	1.6%	5.93	15.2%
Retrofit—Major (marginal): VSS	$20.37	$26.88	0.20	0.5%	6.13	15.7%

Table K-3: Aluminum Production Abatement Option Summary for 2020 World, No-Action Baseline

Reduction Option	Cost(2000$/tCO$_2$eq) DR=10%, TR=40% Low	High	Emissions Reduction of Option (MtCO$_2$eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO$_2$eq)	Cum. % Reduction from 2020 Baseline
Retrofit—Minor: SWPB	–$2.44	$0.73	1.85	2.4%	1.85	2.4%
Retrofit—Minor: VSS	–$5.75	$0.75	8.25	10.7%	10.11	13.1%
Retrofit—Minor: HSS	$0.71	$4.75	2.74	3.6%	12.85	16.7%
Retrofit—Major & Minor: SWPB	$3.97	$5.26	0.00	0.0%	12.85	16.7%
Retrofit—Minor: CWPB	–$16.93	$6.13	4.09	5.3%	16.94	22.0%
Retrofit—Major (marginal): SWPB	$6.27	$6.98	5.56	7.2%	22.50	29.2%
Retrofit—Major & Minor: CWPB	–$14.84	$8.00	0.00	0.0%	22.50	29.2%
Retrofit—Major & Minor: VSS	$7.10	$13.42	0.00	0.0%	22.50	29.2%
Retrofit—Major & Minor: HSS	$9.77	$13.73	0.00	0.0%	22.50	29.2%
Retrofit—Major (marginal): CWPB	–$9.35	$14.17	1.36	1.8%	23.86	31.0%
Retrofit—Major (marginal): HSS	$19.21	$23.25	2.74	3.6%	26.61	34.5%
Retrofit—Major (marginal): VSS	$20.37	$26.88	8.25	10.7%	34.86	45.2%

Table K-4: Aluminum Production Abatement Option Summary for 2020 World, Technology-Adoption Baseline

Reduction Option	Cost(2000$/tCO$_2$eq) DR=10%, TR=40% Low	High	Emissions Reduction of Option (MtCO$_2$eq)	% Reduction from 2020 Baseline	Running Sum of Reductions (MtCO$_2$eq)	Cum. % Reduction from 2020 Baseline
Retrofit—Minor: SWPB	–$2.44	$0.73	1.22	2.7%	1.22	2.7%
Retrofit—Minor: VSS	–$5.75	$0.75	0.20	0.5%	1.43	3.2%
Retrofit—Minor: HSS	$0.71	$4.75	0.80	1.8%	2.23	5.0%
Retrofit—Major & Minor: SWPB	$3.97	$5.26	0.00	0.0%	2.23	5.0%
Retrofit—Minor: CWPB	–$16.93	$6.13	0.26	0.6%	2.48	5.5%
Retrofit—Major (marginal): SWPB	$6.27	$6.98	3.67	8.2%	6.16	13.8%
Retrofit—Major & Minor: CWPB	–$14.84	$8.00	0.00	0.0%	6.16	13.8%
Retrofit—Major & Minor: VSS	$7.10	$13.42	0.00	0.0%	6.16	13.8%
Retrofit—Major & Minor: HSS	$9.77	$13.73	0.00	0.0%	6.16	13.8%
Retrofit—Major (marginal): CWPB	–$9.35	$14.17	0.09	0.2%	6.24	14.0%
Retrofit—Major (marginal): HSS	$19.21	$23.25	0.80	1.8%	7.04	15.7%
Retrofit—Major (marginal): VSS	$20.37	$26.88	0.20	0.5%	7.24	16.2%

Appendix L: Cost and Emissions Reduction Analysis for Options in HCFC-22 Production

L.1 Abatement Option Summary Tables

Table L-1: HCFC-22 Production Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000/tCO_2eq$) DR=10%, TR=40% Low	Cost (2000/tCO_2eq$) DR=10%, TR=40% High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
Thermal Oxidation (New Plants)	$0.23	$0.23	0.00	0.0%	0.00	0.0%
Thermal Oxidation	$0.28	$0.35	110.78	93.9%	110.78	93.9%

Table L-2: HCFC-22 Production Abatement Option Summary: 2010 World, Technology-Adoption Baseline

Reduction Option	Cost (2000/tCO_2eq$) DR=10%, TR=40% Low	Cost (2000/tCO_2eq$) DR=10%, TR=40% High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
Thermal Oxidation (New Plants)	$0.23	$0.23	0.00	0.0%	0.00	0.0%
Thermal Oxidation	$0.28	$0.35	37.52	84.0%	37.52	84.0%

Table L-3: HCFC-22 Production Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000/tCO_2eq$) DR=10%, TR=40% Low	Cost (2000/tCO_2eq$) DR=10%, TR=40% High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
Thermal Oxidation (New Plants)	$0.23	$0.23	21.72	15.8%	21.72	15.8%
Thermal Oxidation	$0.28	$0.35	107.80	78.4%	129.51	94.2%

Table L-4: HCFC-22 Production Abatement Option Summary: 2020 World, Technology-Adoption Baseline

Reduction Option	Cost (2000/tCO_2eq$) DR=10%, TR=40% Low	Cost (2000/tCO_2eq$) DR=10%, TR=40% High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
Thermal Oxidation (New Plants)	$0.23	$0.23	20.49	31.0%	20.49	31.0%
Thermal Oxidation	$0.28	$0.35	37.70	57.0%	58.19	87.9%

Appendix M: Cost and Emissions Reduction Analysis for Options in Semiconductor Manufacturing

M.1 Abatement Option Summary Tables

Table M-1: Semiconductor Production Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO_2eq)	% Reduction from 2010 Baseline	Running Sum of Reductions (MtCO_2eq)	Cum. % Reduction from 2010 Baseline
	Low	High				
Remote Clean	–$67.06	–$67.06	46.37	46.7%	46.37	46.7%
C_3F_8 Replacement	$0.00	$0.00	2.94	3.0%	49.31	49.7%
Capture/Recovery (Membrane)	$4.96	$4.96	11.66	11.8%	60.97	61.5%
Plasma Abatement (etch)	$16.83	$16.83	11.59	11.7%	72.56	73.2%
Thermal Abatement	$24.34	$24.34	4.36	4.4%	76.93	77.6%
Catalytic Abatement	$33.17	$33.17	4.53	4.6%	81.46	82.1%

Table M-2: Semiconductor Production Abatement Option Summary: 2010 World, Technology-Adoption Baseline

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40%		Emissions Reduction of Option (MtCO_2eq)	% Reduction from 2010 Baseline	Running Sum of Reductions (MtCO_2eq)	Cum. % Reduction from 2010 Baseline
	Low	High				
Remote Clean	–$67.06	–$67.06	13.56	36.7%	13.56	36.7%
C_3F_8 Replacement	$0.00	$0.00	0.85	2.3%	14.40	39.0%
Capture/Recovery (Membrane)	$4.96	$4.96	0.40	1.1%	14.81	40.1%
Plasma Abatement (etch)	$16.83	$16.83	2.82	7.7%	17.63	47.8%
Thermal Abatement	$24.34	$24.34	0.69	1.9%	18.32	49.6%
Catalytic Abatement	$33.17	$33.17	0.67	1.8%	18.99	51.5%

Table M-3: Semiconductor Production Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost ($2000\$/tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
	Low	High				
Remote Clean	–$67.06	–$67.06	126.13	54.4%	126.13	54.4%
C_3F_8 Replacement	$0.00	$0.00	7.88	3.4%	134.02	57.8%
Capture/Recovery (Membrane)	$4.96	$4.96	26.35	11.4%	160.37	69.2%
Plasma Abatement (etch)	$16.83	$16.83	31.53	13.6%	191.91	82.8%
Thermal Abatement	$24.34	$24.34	12.67	5.5%	204.57	88.2%
Catalytic Abatement	$33.17	$33.17	13.65	5.9%	218.23	94.1%

Table M-4: Semiconductor Production Abatement Option Summary: 2020 World, Technology-Adoption Baseline

Reduction Option	Cost ($2000\$/tCO_2eq$)		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
	Low	High				
Remote Clean	–$67.06	–$67.06	11.78	41.7%	11.78	41.7%
C_3F_8 Replacement	$0.00	$0.00	0.72	2.5%	12.50	44.2%
Capture/Recovery (Membrane)	$4.96	$4.96	0.00	0.0%	12.50	44.2%
Plasma Abatement (etch)	$16.83	$16.83	1.79	6.3%	14.30	50.5%
Thermal Abatement	$24.34	$24.34	0.16	0.6%	14.46	51.1%
Catalytic Abatement	$33.17	$33.17	0.00	0.0%	14.46	51.1%

Appendix N: Cost and Emissions Reduction Analysis for Options in Electric Power Systems

N.1 Abatement Option Summary Tables

Table N-1: Electrical Power Systems Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000\$/tCO_2eq) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
	Low	High				
Recycling	–\$0.61	–\$0.02	24.12	46.1%	24.12	46.1%
Decommissioning	\$1.47	\$1.47	0.70	1.3%	24.82	47.4%
Leak Detection	–\$0.56	\$2.68	3.45	6.6%	28.26	54.0%
Refurbishment	\$5.01	\$5.01	0.73	1.4%	28.99	55.4%
Awareness/Training	\$5.09	\$5.09	0.25	0.5%	29.24	55.9%
Evacuation	\$23.66	\$23.66	0.01	0.0%	29.26	55.9%
Repair and Replacement	\$45.40	\$45.40	0.04	0.1%	29.30	56.0%

Table N-2: Electrical Power Systems Abatement Option Summary: 2010 World, Technology-Adoption Baseline

Reduction Option	Cost (2000\$/tCO_2eq) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
	Low	High				
Recycling	–\$0.61	–\$0.00	20.03	42.8%	20.03	42.8%
Decommissioning	\$1.47	\$1.47	0.00	0.0%	20.03	42.8%
Leak Detection	–\$0.56	\$2.68	2.36	5.0%	22.39	47.9%
Refurbishment	\$5.01	\$5.01	1.11	2.4%	23.50	50.2%
Awareness/Training	\$5.09	\$5.09	0.00	0.0%	23.50	50.2%
Evacuation	\$23.66	\$23.66	0.00	0.0%	23.50	50.2%
Repair and Replacement	\$45.40	\$45.40	0.00	0.0%	23.50	50.2%

Table N-3: Electrical Power Systems Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost ($2000\$/tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % 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 N-4: Electrical Power Systems Abatement Option Summary: 2020 World, Technology-Adoption Baseline

Reduction Option	Cost ($2000\$/tCO_2eq$) DR=10%, TR=40%		Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % 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%

Appendix O: Cost and Emissions Reduction Analysis for Options in Magnesium Production

O.1 Abatement Option Summary Tables

Table O-1: Magnesium Production Abatement Option Summary: 2010 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
SO_2 Replacement	$0.53	$0.79	6.88	56.8%	6.88	56.8%
Fluorinated Cover-gas	$1.21	$1.48	5.07	41.9%	11.94	98.7%

Table O-2: Magnesium Production Abatement Option Summary: 2010 World, Technology-Adoption Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2010 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2010 Baseline
SO_2 Replacement	$0.53	$0.79	2.54	71.5%	2.54	71.5%
Fluorinated Cover-gas	$1.21	$1.48	0.86	24.3%	3.40	95.8%

Table O-3: Magnesium Production Abatement Option Summary: 2020 World, No-Action Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
SO_2 Replacement	$0.53	$0.79	10.90	60.3%	10.90	60.3%
Fluorinated Cover-gas	$1.21	$1.48	6.95	38.5%	17.85	98.8%

Table O-4: Magnesium Production Abatement Option Summary: 2020 World, Technology-Adoption Baseline

Reduction Option	Cost (2000$/$tCO_2eq$) DR=10%, TR=40% Low	High	Emissions Reduction of Option ($MtCO_2eq$)	% Reduction from 2020 Baseline	Running Sum of Reductions ($MtCO_2eq$)	Cum. % Reduction from 2020 Baseline
SO_2 Replacement	$0.53	$0.79	4.19	86.6%	4.19	86.6%
Fluorinated Cover-gas	$1.21	$1.48	0.44	9.2%	4.63	95.8%

Appendix P: Summary of Non-CO_2 Agricultural Mitigation Analysis Completed for EMF-21

This analysis, summarized in Table P-1, was used by modelers participating in EMF-21 to represent the agricultural sector in multigas and multisectoral mitigation analyses. Cost estimates (in USD/tonne carbon equivalent [tCeq]) were developed for mitigating N_2O from cropland soils and mitigating CH_4 from livestock enteric fermentation, manure management, and rice cultivation for major world regions. Mitigation options include reducing applications of nitrogenous fertilizers (for soil N_2O), improving feed intake efficiency, and increasing animal productivity (for enteric CH_4), using anaerobic digesters (for manure CH_4), and changing water management regime and fertilizers (for rice CH_4). Total estimated global mitigation potential is approximately 64 MtC (235 $MtCO_2eq$) in 2010 at negative or zero costs, 141 MtC (518 $MtCO_2eq$) at $200/tC ($55/tCO_2eq), and up to 168 MtC (617 $MtCO_2eq$) at higher costs. Costs for individual options ranged from negative to positive in nearly every region, depending on emissions reduction and changes in yield, input, labor, capital cost, and outside revenue effects.

Table P-1: Maximum Agricultural CH_4 and N_2O Mitigation Results in 2010 by Region (Over Entire Cost Range, ≤ $50/tCeq to > $200/tCeq)

	Soil N_2O		Enteric CH_4		Rice CH_4		Manure CH_4	
Region	**tCeq**	**2010 Baseline (Percent)**	**tCeq**	**2010 Baseline (Percent)**	**tCeq**	**2010 Baseline (Percent)**	**tCeq**	**2010 Baseline (Percent)**
United States	7.8	9.0%	1.8	5.0%	—	—	1.80	16.0%
EU-15	4.3	9.0%	3.7	11.0%	—	—	1.60	16.0%
Japan	0.2	61.0%	0.2	11.0%	—	—	0.03	16.0%
Russia	1.8	12.0%	2.9	13.0%	—	—	0.30	13.0%
CIS	1.4	12.0%	1.5	13.0%	—	—	0.20	16.0%
Brazil	1.1	2.0%	0.6	1.0%	—	—	0.50	19.0%
Other Latin America	1.0	2.0%	0.6	1.0%	—	—	0.40	19.0%
China	15.6	10.0%	3.7	6.0%	24.1	35%	1.50	19.0%
India	14.1	13.0%	5.3	10.0%	10.2	37%	1.60	19.0%
Other Asia	7.1	13.0%	3.2	6.0%	25.7	38%	1.40	19.0%
Africa	0.2	0.1%	2.7	3.0%	—	—	0.80	19.0%
Global Total[a]	**62.9**	**8.0%**	**33.9**	**6.0%**	**61.0**	**33%**	**11.40**	**17.0%**

Source: DeAngelo et al., 2006.
CIS = Commonwealth of Independent States; EU-15 = European Union.
[a] Global total includes all regions listed here, in addition to other regions for which these EMF regional results were extrapolated.

The EMF-21 analysis (DeAngelo et al., 2006) used similar methods to those described in this report. The approach also used an engineering, bottom-up approach with input parameters from a small number of agricultural greenhouse gas mitigation studies in the literature; FAOSTAT, baseline emissions and activity data constructed by Scheehle and Kruger (2006); and, in some cases, IPCC default emissions factors. Mitigation options were selected for cropland soil N_2O (from Bates [2001], AEA Technology Environment [1998]), enteric CH_4 (from Johnson et al. [2003a], [2003b], Bates [2001], Gerbens [1998]), rice CH_4 (from Wassmann et al. [2000], Van der Gon et al. [2001]), and manure CH_4 (from Bates [2001], USEPA AgStar [2003]). The current analysis uses a similar set of mitigation options but applies the options differently, such that associated GHG effects, yield changes, costs, and penetration by region are not the same. Figure P-1 compares the global agricultural MAC curve (summing across all agricultural sectors included in the analysis) estimated in the EMF-21 analysis with MAC curves estimated in the current analysis. For the current analysis, curves are presented both with number of animals and crop area held constant and with commodity production held constant. Figure P-2 presents this comparison in terms of percentage emissions reductions from baseline. The baseline emissions being used for this analysis are lower than for EMF-21, leading to a greater difference between EMF-21 and the current analysis in percentage terms than absolute reductions.

Figure P-1: Comparison of 2010 Global Agricultural MAC Curves for EMF-21 and Current Analysis: Absolute Emissions Reductions

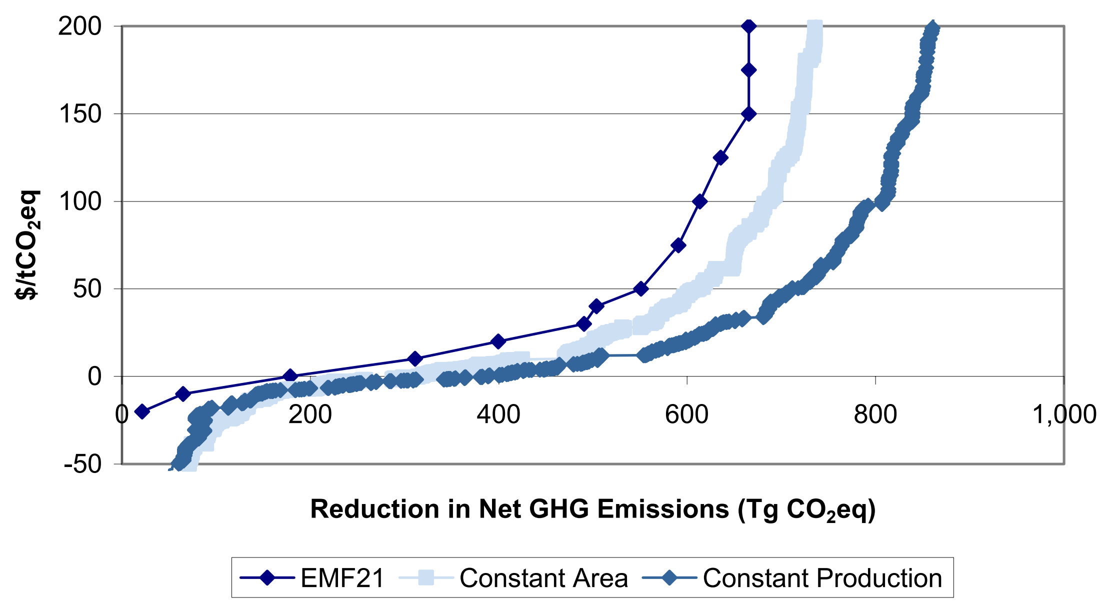
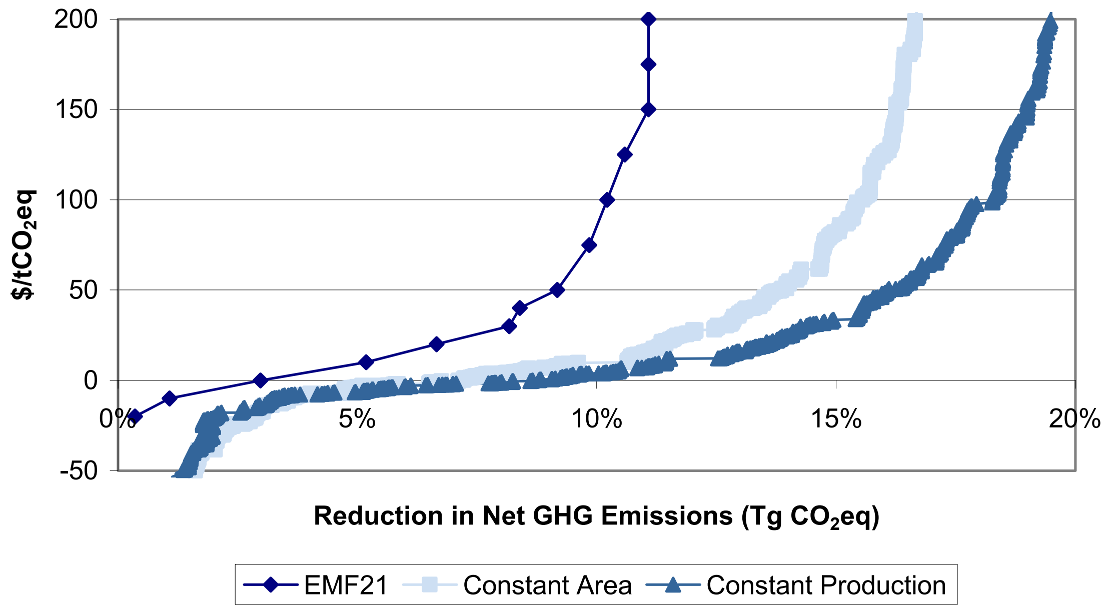


Figure P-2: Comparison of 2010 Global Agricultural MAC Curves for EMF-21 and Current Analysis: Percentage Emissions Reductions from Baseline



Appendix Q: DAYCENT Model Description and Methods

DAYCENT (Del Grosso et al., 2001; Parton et al., 1998) was used to simulate fluxes of N_2O between mineral agricultural soils and the atmosphere for lands where major crop types (e.g., corn, soybean, wheat, alfalfa hay, other hay, silage, cotton, and sorghum) are grown. DAYCENT simulates biogeochemical nitrogen fluxes between the atmosphere, vegetation, and soil, allowing for a dynamic representation of greenhouse gas fluxes that accounts for environmental conditions, soil characteristics, climate, specific crop qualities, and management practices at a daily time step. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Nutrient supply is a function of soil organic matter decomposition rates and external nutrient additions. Daily maximum/minimum temperature and precipitation, timing, description of management events (e.g., fertilization, tillage, harvest), and soil texture data are model inputs. Key submodels include plant production, organic matter decomposition, soil water, soil temperature by layer, nitrification and denitrification, and CH_4 oxidation. Comparison of model results and plot-level data show that DAYCENT reliably simulates crop yields, soil organic matter levels, and trace gas fluxes for a number of native and managed systems (Del Grosso et al., 2001, 2005) found in the United States.

In DAYCENT, once nitrogen enters the plant/soil system, the model cannot distinguish the original source of the nitrogen from which the N_2O emissions are derived. This means, for example, that N_2O emissions from applied nitrogen fertilizer cannot be separated from emissions due to nitrogen inputs from crop residue. Consequently, emissions cannot be partitioned into the IPCC recommended categories (i.e., synthetic fertilizer, organic fertilizer, sewage sludge, and crop residues). Nitrogen losses from major crops due to volatilization and leaching/runoff processes are calculated within DAYCENT based on current conditions. As a result, fertilizer applications have not been reduced by the IPCC default volatilization factors for major crop types—those loss processes are, instead, simulated within the model.

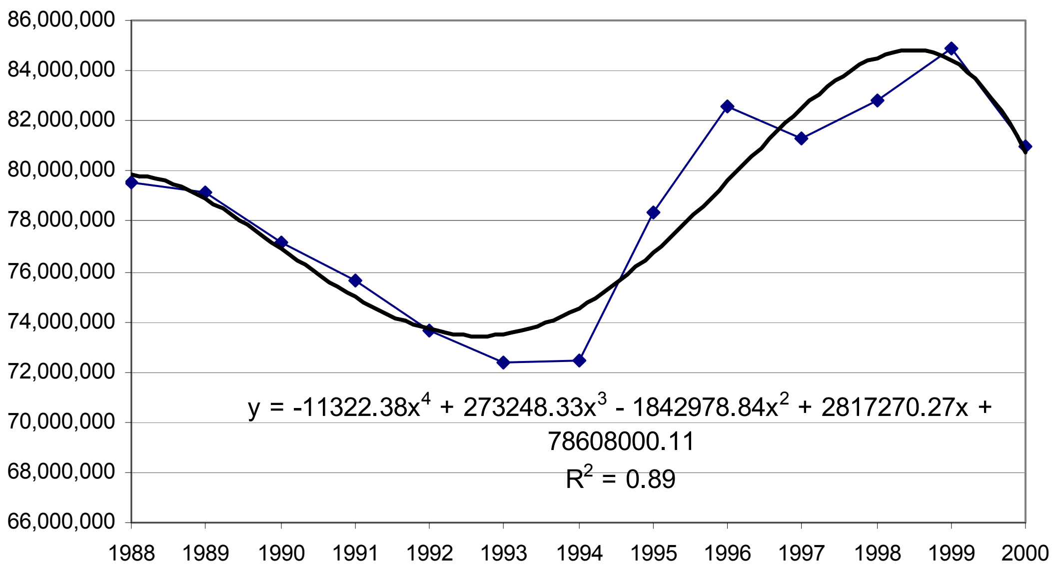
DAYCENT's simulation of indirect N_2O emissions accounts for volatilization and leaching/runoff from all nitrogen in the soil system, regardless of the source of that nitrogen, according to specific environmental and management conditions. N_2O is emitted indirectly from nitrogen applied as commercial fertilizer, sewage sludge, and livestock manure, and from other management practices (e.g., plowing, irrigating, harvesting). Nitrogen from managed manure not applied to crops (or pastures) was assumed to volatilize before application to soils.

While DAYCENT simulates NO_x and NH_3 volatilization, as well as NO_3 leaching/runoff, it does not model their transport or subsequent off-site conversion to N_2O.

Much of the global spatial data (vegetation and soil) were obtained from the Potsdam NPP simulations (Cramer et al., 1999). Daily weather data were obtained from National Centers for Environmental Prediction (NCEP), with a 1.9° resolution. Weather from 1991 to 2000 was used for all baseline and experimental runs so that long-term trends in weather would not influence N_2O emissions and interannual variability would be retained. The native vegetation and soils maps were also used from the Potsdam application and were converted from the 5° resolution to 1.9° resolution by overlaying the NCEP grid and selecting modal vegetation or soil types that fell within the 1.9° NCEP cell.

Two global vegetation maps were compared with regard to the distribution of native vegetative and agricultural land: GLC 2000 and IGBP. After finding that neither was a superior choice, the maps were combined to maximize the potential cropping area. A fractional area of crop types was also available from IGBP, which was used to determine the total fraction of cropped area within a grid cell. Cells with less than 5 percent agriculture were masked to reduce simulation time. Crop area was assumed to have peaked globally during the 1990s, so area remained constant throughout the simulations. Total crop area was validated by comparing estimated crop area with reported country-level crop area from the FAO for 2000. Comparisons showed nearly 1:1 relationships among the four crop groups. Figure Q-1 shows the trend in global consumption of nitrogen fertilizer from 1988 through 2000.

Figure Q-1: Global Consumption of Nitrogen is a Curvilinear Trend from 1988–2000. The Trend is Described by a 4th Order Polynomial



Nominal crop and region-specific nitrogen addition rates were based on analysis performed at Kassel University (Stehfest et al., personal communication). Country-level nitrogen inputs based on these nominal rates were compared with data from FAO, IFA, and Bouwman et al. (2005). The FAO (FAOSTAT, 2004a, 2004b) provides data on crop-specific production or yield but reports only total nitrogen consumption at the country level. However, it was necessary to identify crop-specific rates of fertilizer application to accurately model crop yields and N_2O emissions. An IFA (IFA, 2002) paper on crop-specific fertilizer use was available but did not report every country for every year between 1990 and 2000; therefore, the available data were compared with FAO production data to establish regression equations. The IFA data on fertilizer use were entered into a database and compared with FAO production data to establish regression equations between crop yield and fertilizer application rate. These regression equations were then used to correct the nominal crop/country-specific fertilizer inputs used to drive the simulations. However, further research yielded a report by the FAO (2000) (*Fertilizer Requirements in 2015 and 2030*) in which this very procedure was used to report crop-specific fertilizer rates. Therefore, these equations (Table Q-1) replaced the independently derived equations. No equation was available for soybeans, and independent regressions showed that production was invariant to fertilizer rate (because soybeans are nitrogen fixers). Therefore, we used Elke's rates for soybean fertilization, and subsequent scalars were assumed to be constant for this crop only.

There is no global database on temporal use of organic matter additions. However, organic fertilizer can be assumed to be a function of animal numbers within each country. The average manure applications were calculated outside the project, originally derived from Siebert et al. (personal

Table Q-1. FAO Equations for Predicting Fertilizer Rate (Kg/Ha) Based on Yield (t/ha) for Wheat and Maize

Crop Group	Production (y) (Mt) = a + b × fertilizer (Mt) (x)	R^2
Wheat	y = 2.65 + 22.43 × x	0.80
Maize	y = –15.43 +23.14 × x	0.76
Soybean	y = 5,797.7 + 18.676 × x	0.063

Source: FAO, 2000; FAOSTAT, 2004b; IFA, 2002.

[a] Equation for soybeans based on combination of FAOSTAT and IFA. Crop-specific estimates were assumed to be representative of analogous crops as well.

communication) based on 12 animal types and their specific nitrogen excrement. The nitrogen production per animal type and month was calculated according to temperature, feed type shares, and grazing/barn priorities. Manure nitrogen from barns was assumed to be distributed evenly (kg/hectare) across grass and crop types.

These initial manure-nitrogen application rates were assumed to be base rates, representative of current trends in organic fertilizer management. Historical trends in organic fertilizer use were calculated from animal numbers reported by the FAO, using IPCC constants concerning region-specific average nitrogen excretion per animal (Table Q-2) and the percentage of nitrogen distributed among waste management practices.

Table Q-2: Default Values for Nitrogen Excretion per Head of Animal per Region (Kg/Animal/Year) from the IPCC

Region	Type of Animal					
	Nondairy Cattle	Dairy Cattle	Poultry	Sheep	Swine	Others
North America	70	100	0.6	16	20	25
Western Europe	70	100	0.6	20	20	25
Eastern Europe	50	70	0.6	16	20	25
Oceania	60	80	0.6	20	16	25
Latin America	40	70	0.6	12	16	40
Africa	40	60	0.6	12	16	40
Near East and Mediterranean	50	70	0.6	12	16	40
Asia and Far East	40	60	0.6	12	16	40

Source: IPCC, 1996.

Because we are only interested in manure used in fertilizing agricultural fields, total manure nitrogen was calculated using the daily spread, solid storage per drylot, and liquid systems (i.e., slurry) from the animal waste management systems described above. Animal numbers were retrieved from FAOSTAT from 1961 to 2000, and only cattle, poultry, sheep, and swine were used in the calculations. Beef versus dairy cattle were assumed to be 50/50 of the cattle numbers reported by the FAO. Calculations were done on a regional basis (e.g., North America, Western Europe) to aid in the speed of calculations and for direct comparison to the categories used by the USEPA. A global total was computed and assessed for a global maximum (1983). Trends in crop area for cereals and soybeans were also calculated for the regions, and total nitrogen was divided by the crop area as a rough correction for the increase in crop area over time. Scalars were then computed by dividing the yearly estimates by the global maximum. Figures Q-2, Q-3, and Q-4 map N_2O emissions rates around the globe for wheat, maize, and soybeans, respectively. These maps reveal sharp differences in emissions rates due to differences in cropping patterns, fertilizer use, climate, and cultivation practices.

Figure Q-2: DAYCENT-NCEP Global Simulation: Wheat N_2O Emissions: 1991–2000

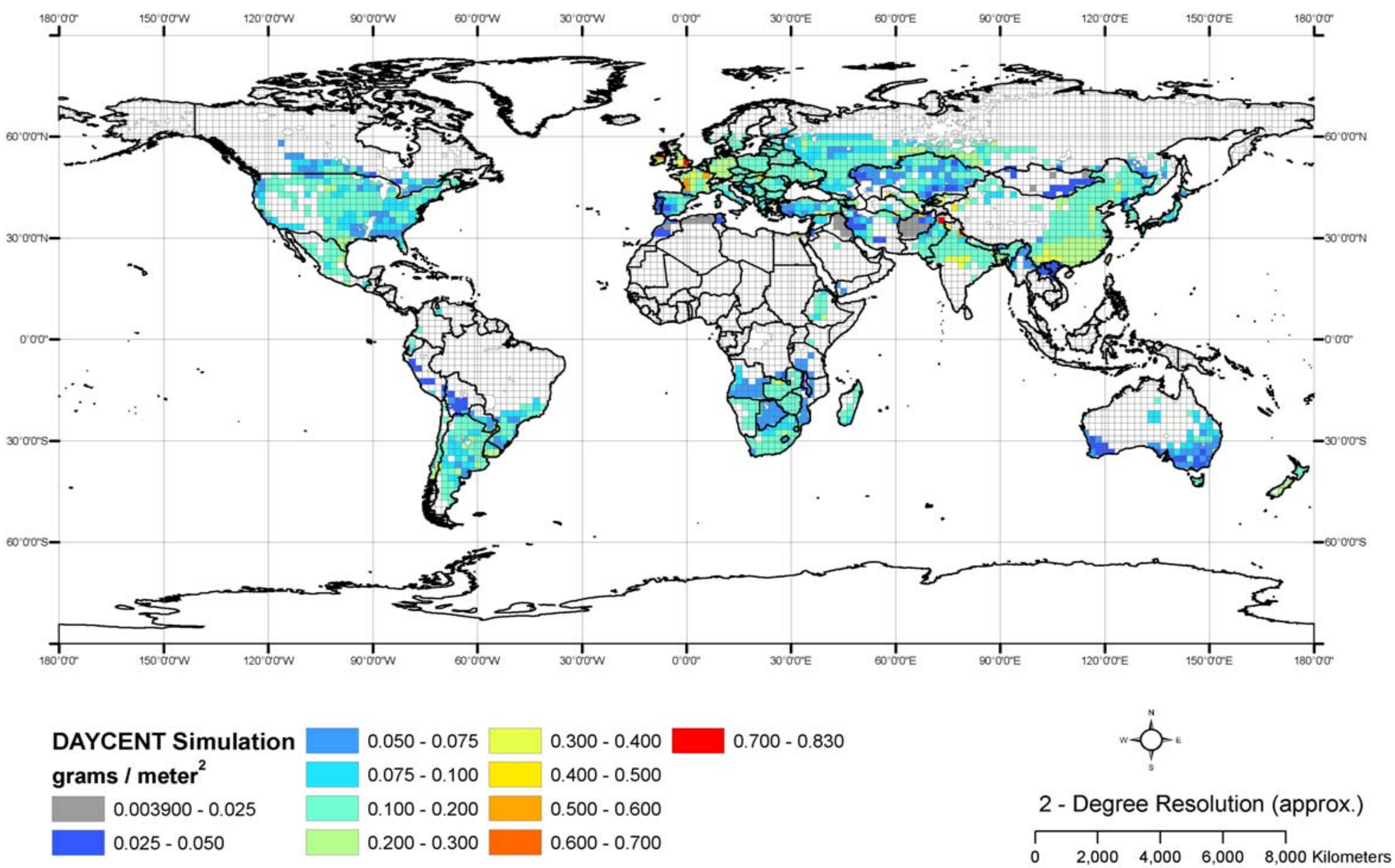


Figure Q-3: DAYCENT-NCEP Global Simulation: Maize N_2O Emissions: 1991–2000

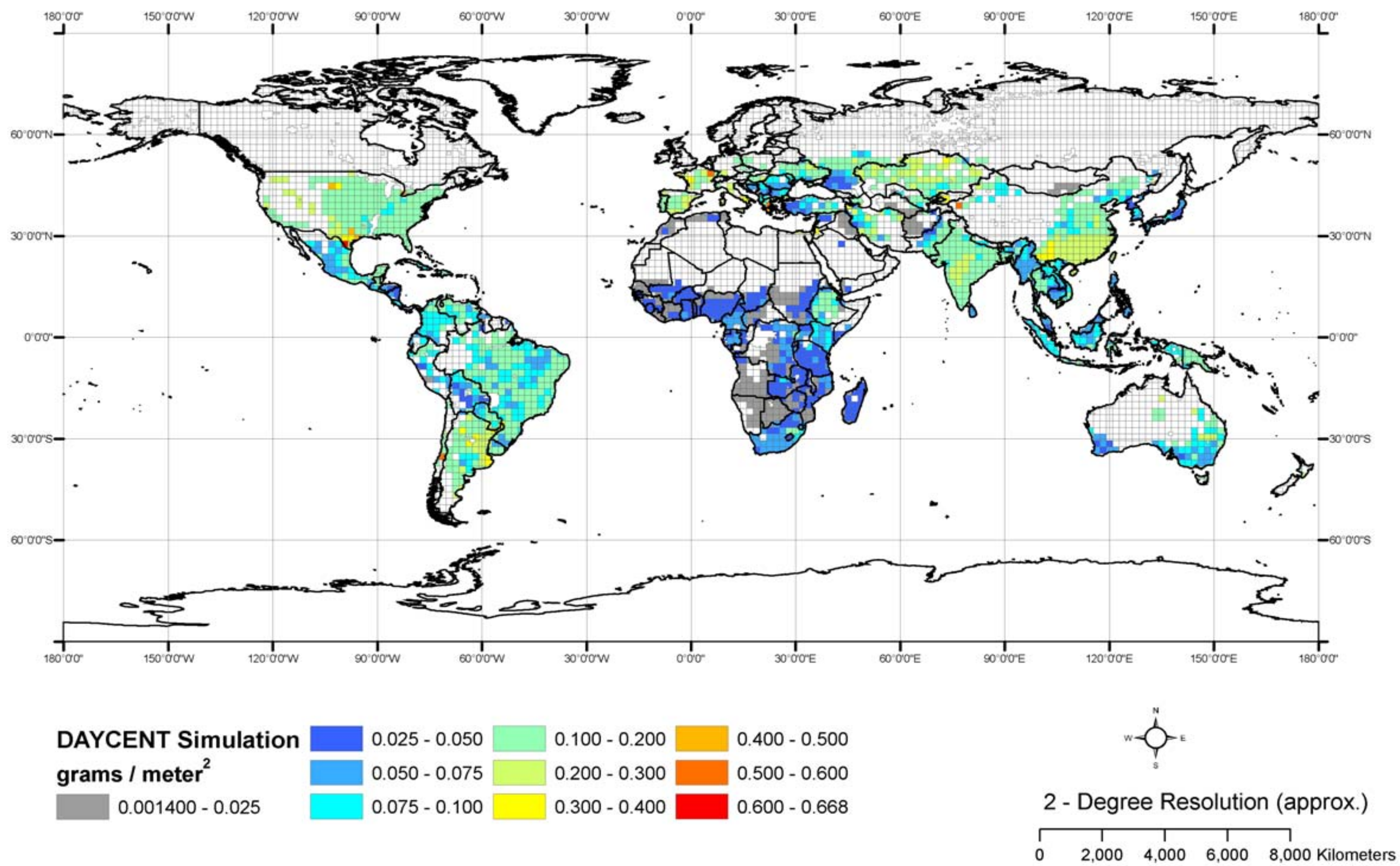
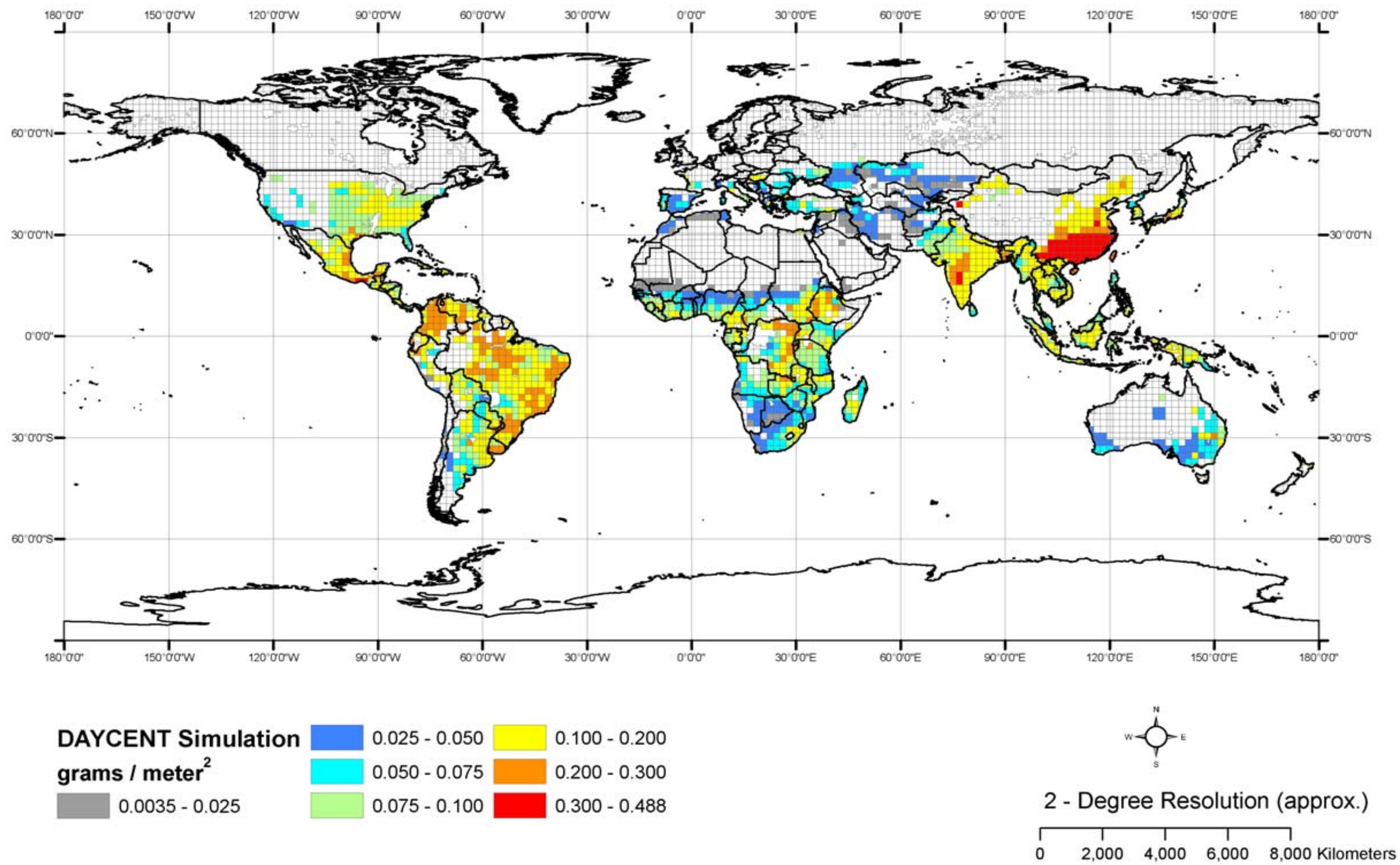


Figure Q-4: DAYCENT-NCEP Global Simulation: Soybean N_2O Emissions: 1991–2000



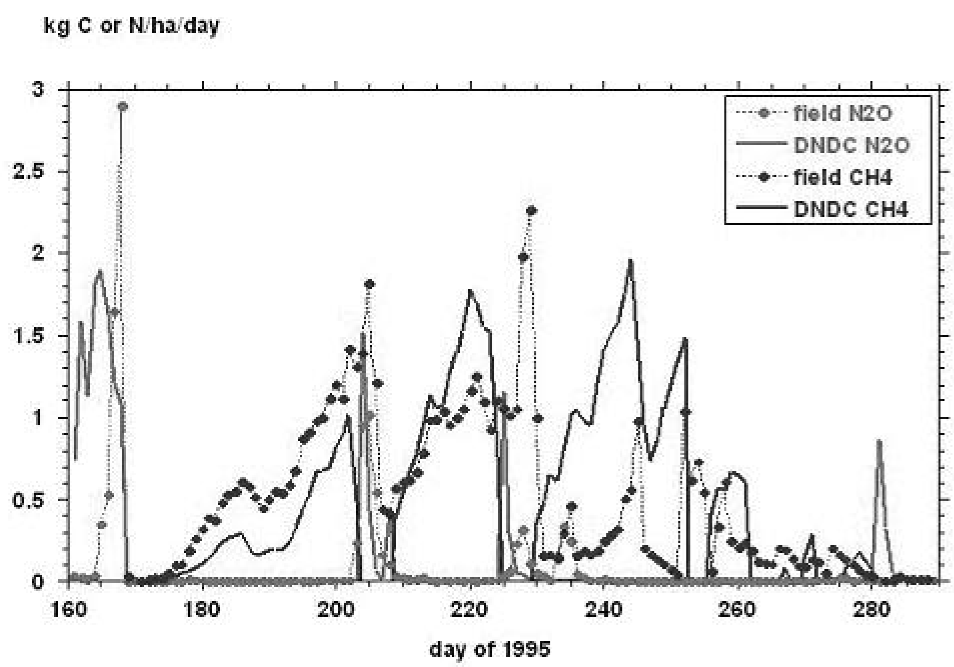
Appendix R: DNDC Model Description and Methods

DNDC has been used to estimate carbon sequestration; nitrate leaching; and emissions of N_2O, NO, CH_4, and NH_3 in agricultural lands in the United States and China. DNDC estimates of N_2O and CH_4 have been independently tested and validated for a number of different world regions and are now used for national trace gas inventory studies in the United States, Canada, the United Kingdom, Germany, Italy, Belgium, New Zealand, China, Japan, India, Thailand, and the Philippines.

DNDC requires data on soils (e.g., pH, soil carbon, bulk density, and soil texture), rice cropping areas and systems (e.g., singe rice, double rice, rice rotated with upland crops), climate, and management practices (e.g., fertilizer use, planting and harvesting dates, tillage, water use).

This new DNDC model has been tested against several methane flux data sets from wetland rice sites in the United States, Italy, China, Thailand, and Japan (Li et al., 2002; Cai et al., 2003). Both CH_4 and N_2O fluxes were measured at five of the tested rice paddy sites where midseason drainage was applied (Zheng et al., 1997; Cai et al., 1999). DNDC was tested against the observations from the five sites in China with satisfying results (Cai et al., 2003). A validation case is shown in Figure R-1, which demonstrates a fair agreement between observed and DNDC-modeled CH_4 and N_2O fluxes regarding their patterns and magnitudes for a rice paddy field applied with midseason drainage in Wu County, Jiangsu Province, China in 1995. The results from the tests indicate that, with discrepancies for only about 20 percent of the tested cases, DNDC is capable of estimating the seasonal patterns and magnitudes of CH_4 and N_2O fluxes from the sites.

Figure R-1: Comparison Between Observed and DNDC-Modeled CH_4 and N_2O Fluxes



DNDC captured the episodes of CH_4 emissions depressions and N_2O emissions increases during the soil-drying periods by tracking the soil reduction potential dynamics, CH_4 oxidation, labile organic-matter decomposition, and stimulated nitrification and denitrification fueled by the increased ammonium and nitrate production because of the conversions of soil anaerobic to aerobic conditions. These conversions were driven by the midseason drainage (field data were adopted from Zheng et al. [1997]).

For this analysis, we built and used geographic information systems (GIS) databases for China at a county scale. Therefore, we assumed the soil, climate, and management conditions were the same within each county but varied from one county to the next based on our input data. For each baseline time period, we ran the DNDC model for 21 years (2000 through 2020) for each of the approximately 2,500 counties in China to simulate changes in soil carbon, emissions of CH_4 and N_2O, and rice yields. After running the model at the county scale, we aggregated the county results to the national scale.

The soil databases contain maximum and minimum values for each soil parameter. We used an MSF approach to estimate the range in greenhouse gas emissions for each county. Based on sensitivity tests to prioritize the environmental factors, including soil properties, temperature, and precipitation (Li et al., 2004), the most sensitive factors for CH_4 and N_2O emissions from rice paddies are soil texture and soil organic carbon content, respectively. Therefore, by varying these MSFs, namely soil texture and soil organic carbon, over the ranges reported in the county-scale database, we produced a range of CH_4 and N_2O emissions for each cropping system in each county. We report emissions estimates in ranges to capture the uncertainty in emissions due to our input data. The MSF method has been validated against a traditional uncertainty analysis approach, such as Monte Carlo analyses (Li et al., 2004). In addition, we ran each scenario with and without midseason drainage to provide flexibility in defining nominal adoption of midseason drainage and to examine the impact of using midseason drainage coupled with other mitigation options.

Soil manganese (MN), iron (Fe), and sulfate content were set to average values for Chinese paddy soils: Mn = 30 mg kg-1 soil, Fe = 80 mg kg-1 soil, and sulfate = 220 mg kg-1 soil (Li, 1992).

Because most farmers traditionally have lacked the appropriate machinery to properly chop and reincorporate rice residue back into the soils and either burn or use the above-ground residue for off-field uses, we assumed that only 15 percent of the above-ground residue remained on-site in China in 2000. However, because of recent air quality problems, the Chinese government is moving toward banning burning of crop residues. Therefore, we assumed that above-ground residue incorporation will increase an average of 5 percent per year until a maximum of 50 percent residue incorporation is reached in 2007. From 2007 through 2020, we assumed 50 percent residue incorporation. For the rest of the Asian countries simulated, we assumed that 10 percent of the above-ground residue was incorporated after harvest throughout the 21-year period used for the analysis. All below-ground biomass (i.e., roots) remained in the soil following harvest.

As indicated in Section V.1.3.2, China was the focus area of the rice analyses with DNDC partly because DNDC has been tested rigorously for China's rice paddies and because there is a detailed GIS database on soils and climate. Figure R-2 summarizes the findings for impacts of management alternatives on greenhouse gas emissions in China. Although we recognize one of the major strengths of using process-based biogeochemical models is the ability to capture the influence of site-specific conditions (soils and climate, for example) on greenhouse gas emissions under various management regimes, we used DNDC to estimate impacts of the mitigation options across a series of sites throughout Asia (see Table R-1). The goal was not to estimate total emissions under each mitigation option country by country, but rather to assess the relative impact of each mitigation option across a broad range of soils

Figure R-2: Impacts of Management Alternatives on Nationally Averaged GWPs of Rice Paddies in China, 2000–2020

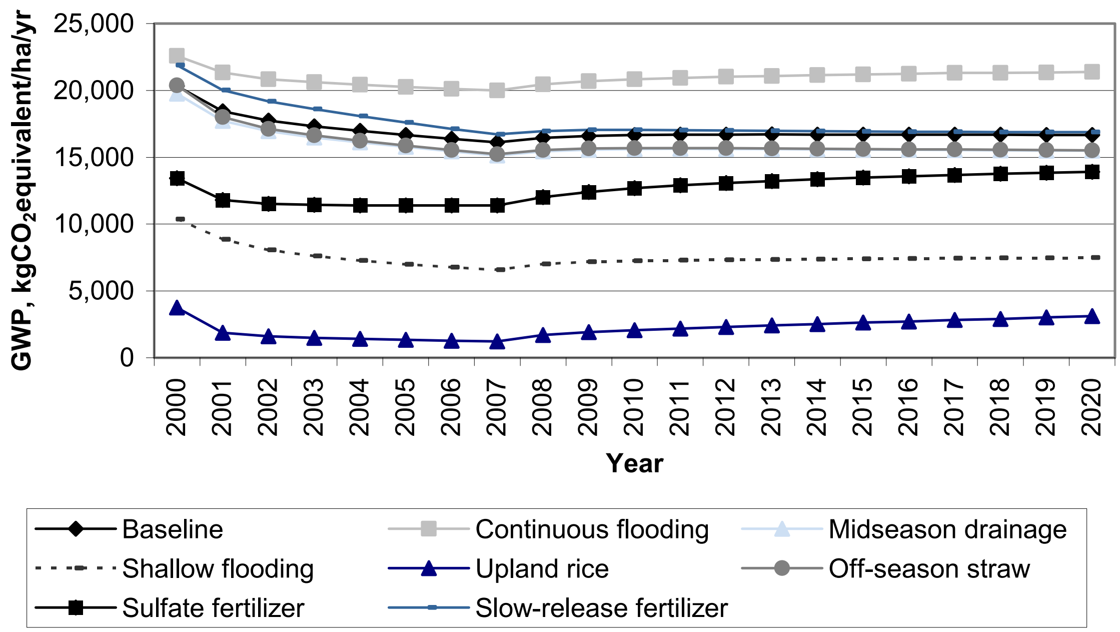


Table R-1: Sites Used for Country-Specific Mitigation Analyses

Name	Country	Latitude	Soil Carbon (%)	Clay Fraction	Rice
Kalasin	Thailand	16.6º	2.30	0.27	Irrigated
Delhi	India	28.0º	0.45	0.19	Irrigated
Punjab	India	32.0º	0.60	0.27	Irrigated
Kerala	India	12.4º	1.40	0.49	Rain-fed
Udon Thani	Thailand	17.4º	2.30	0.41	Rain-fed
Rajshahi	Bangladesh	24.6º	1.60	0.49	Irrigated
Rangpur	Bangladesh	25.7º	2.50	0.43	Rain-fed
Aceh	Indonesia	4.3º	3.80	0.27	Irrigated
Sumatera	Indonesia	2.3º	7.00	0.27	Rain-fed
Pagasinan	Philippines	16.0º	2.00	0.34	Rain-fed
Isabela	Philippines	17.0º	2.00	0.27	Irrigated
Habac	Vietnam	21.3º	1.90	0.63	Irrigated
Caobang	Vietnam	22.7º	1.50	0.27	Rain-fed
Niigata	Japan	37.5º	3.20	0.35	Irrigated

and climate conditions found in Asia. We should also note that for the site analyses for Delhi, Punjab, and Kerala, we used an India-specific rice crop model that was developed based on the calibration and validation studies of Pathak et al. (2005) and Babu et al. (2005). For all other countries, we used the China rice crop model.

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, soils and climate data were compiled from several sources. Soil bulk density (in grams per cubic centimeter to 100 cm soil depth) was extracted from the 5 arc-minutes (approximately 10 km) IGBP-DIS Global Gridded Surfaces of Selected Soil Characteristics data. Soil pH at two depths (0 to 30 cm and 30 to 100 cm) were used to provide estimates of maximum and minimum soil pH. These pH data were derived from the ISRIC-WISE 0.5-Degree Global Data Set of Derived Soil Properties. Soil texture was extracted from the Global Soil Texture and Derived Water-Holding Capacities database (Webb et al., 2000). These soils databases were obtained from the Oak Ridge National Laboratories (ORNL) DAAC Soil Collections Web site. NOAA's National Center for Environmental Prediction data were used for daily minimum and maximum temperature, precipitation, and solar radiation (Kistler et al., 2001). Data from IFPRI's IMPACT model were used to develop region-specific changes in optimal yields over time for use in DNDC, as shown in Table R-2. Actual yields may increase less than these values, which serve as an upper bound on yield increases. For those Asian regions where DNDC simulations are not carried out, DNDC yield and emissions are used as proxies, as shown in Table R-3.

Table R-2: Region-Specific Optimal Yield Increases Used for DNDC Simulations, 2000–2020

Country	Percent
Japan	4%
India	33%
Bangladesh	31%
Indonesia	23%
Thailand	16%
The Philippines	29%
Vietnam	37%

Source: IMPACT model results

Table R-3: Areas Used to Proxy Yield and Emissions Changes for Regions Not Directly Modeled with DNDC

Region	Areas Used
Malaysia	Average of Indonesia, the Philippines, and Thailand
Myanmar	Average of Bangladesh and Thailand
South Korea	Average of Chinese subregions Haihe and Songliao
Other Southeast Asia	Average of Thailand and Vietnam

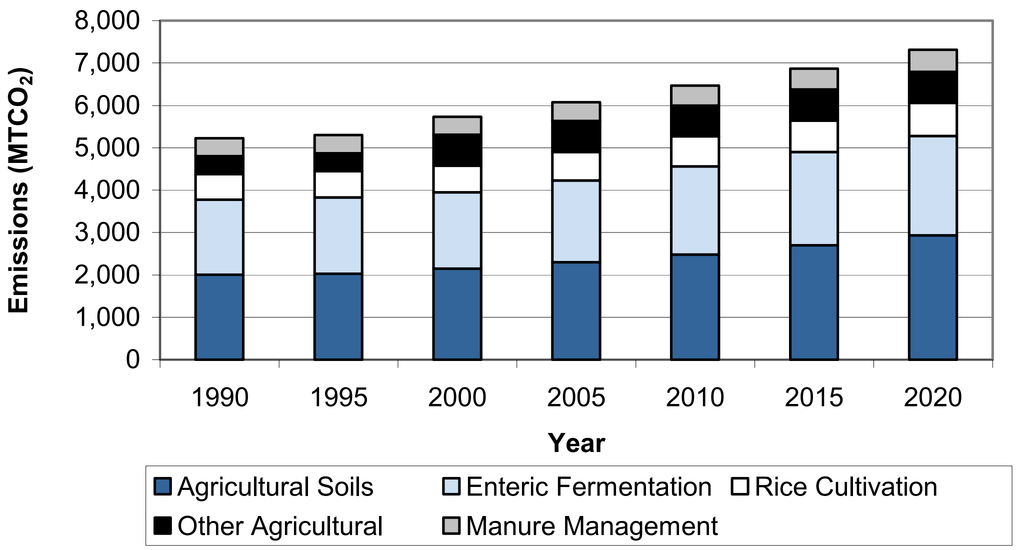
Appendix S: Baseline Differences and Methods for This Mitigation Analysis

Although this mitigation analysis uses different baseline methods and assumptions from those used in the USEPA (2006) for agricultural soil emissions and for rice cultivation emissions, the baseline emissions and activity data used for the mitigation analysis of livestock enteric and manure emissions are the same. This appendix provides an overview comparison of the baseline emissions, projections, and methods between the *Global Non-CO_2 Emissions Report* and this mitigation analysis.

S.1 Baseline Estimates and Projections by the USEPA *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions* Report

The baseline emissions projections for agricultural soil management (N_2O); rice cultivation (CH_4); livestock enteric fermentation (CH_4); livestock manure (CH_4); and other agricultural sources (CH_4 and N_2O), including residue burning, savannah burning, and open burning for forest clearing, have been estimated by the USEPA (2006) for 1990 through 2020. Figure S-1 summarizes these results.

Figure S-1: Global Agricultural Non-CO_2 Emissions Estimated by the USEPA



Source: USEPA, 2006.

The USEPA *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions Report* (USEPA, 2006) compiles and estimates agricultural (and other sectoral) non-CO_2 emissions using publicly available reports prepared in-country (e.g., National Communications submitted to the Climate Secretariat of the United Nations Climate Change Conference [UNFCCC]), or, where such in-country data are not available, with IPCC Tier I default emissions factors and activity data (e.g., fertilizer production, livestock populations) from FAO and IFPRI. In this analysis, we use the livestock emissions from the USEPA (2006) but develop different baselines for rice cultivation and agricultural soil management. Tables S-1 and S-2 compare the baseline emissions and methods between the USEPA (2006) and this report.

Table S-1: Comparison of Baseline Emissions Estimation Methods Between *Global Non-CO_2 Emissions Report* and This Study

Emissions Source	*USEPA Global Non-CO_2 Emissions Report*	This Study
Agricultural soils	*Estimates compiled* from national communications, country study reports, and ALGAS reports *Data/method:* if not publicly available, report includes FAO projection of fertilizer production, IFPRI projection of livestock population, IPCC Tier I default emissions factors *Direct emissions* include fertilizer applications, nitrogen-fixing crops, incorporation of crop residues, histosols, livestock waste on croplands and pasture, and direct deposition of waste by livestock *Indirect emissions* include volatilization and subsequent atmospheric deposition of NH_4 and NO_x originating from direct nitrogen inputs Includes N_2O emissions associated with *rice* cultivation	*DAYCENT* model generated N_2O and soil carbon emissions for all world regions *Data inputs* include soils database from FAO/UNESCO; daily weather from NOAA/NCEP; crop area from a combination of IGBP and GLC2000 land cover classification; historic fertilizer nitrogen from IFA, 2002, FAOSTAT, 2004, and University of Kassel; projected fertilizer nitrogen from FAO 2000 yield-nitrogen relationships and IFPRI yield projections; manure nitrogen from FAOSTAT and the USEPA/*Global Emissions Report* projections *Direct emissions* same as *Global Emissions Report* but includes smaller number of nitrogen-fixing crops, does not include histosols or any livestock waste on pasture or grazing lands *Indirect emissions* categories same as *Global Emissions Report* Focus on *wheat, maize, and soybeans*, not on entire cropland base Excluded N_2O emissions associated with *rice* cultivation
Rice	*Estimates compiled* from national communications, country study reports, and ALGAS reports *CH_4 only* *Projection method*: if not publicly available report includes rice area from FAOSTAT 2001, water management regime from IRRI, scaling to UN 2002 population projections, IPCC Tier I default emissions factors	*DNDC* model generated *CH_4, N_2O, and soil carbon* emissions for *Asia only* National data on soils, rice systems, and management incorporated into DNDC Rice area remains fixed over time
Enteric	*Estimates compiled* from national communications, country study reports, and ALGAS reports	Same
Manure	*Estimates compiled* from national communications, country study reports, and ALGAS reports	Same

Table S-2: Comparison of Global Baseline Emissions Estimates: *Global Anthropogenic Non-CO_2 GHG Emissions Report* and This Study

	CH_4 Estimates ($MtCO_2eq$)						N_2O Estimates ($MtCO_2eq$)						Soil Carbon Included	
	2000		2010		2020		2000		2010		2020			
Emissions Source	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**	**USEPA (2006)**	**This Study**
Agriculture soils	N/A	N/A	N/A	N/A	N/A	N/A	2,146	799	2,482	795	2,937	859	N	Y
Rice	634	747	708	818	776	862	N/A	280	N/A	164	N/A	150	N	Y
Enteric	1,799	Same	2,079	Same	2,344	Same	N/A	N/A	N/A	N/A	N/A	N/A	N	N
Manure	225	Same	244	Same	269	Same	196	Same	226	Same	254	Same	N	N

N/A = Not applicable.

S.2 N_2O Emissions from Agricultural Soil Management

The largest global source of agricultural non-CO_2 emissions is the release of N_2O through the management of soils. According to the USEPA (2006), in 2000, global N_2O emissions were estimated to be 6,922 Gg or 2,146 $MtCO_2eq$ and are projected to increase 37 percent by 2020 to 9,474 Gg or 2,937 $MtCO_2eq$ (a 47 percent increase relative to 1990). Agricultural soil N_2O emissions accounted for 40 percent of global agricultural non-CO_2 emissions in 2000. In the United States, agricultural soil N_2O annually accounts for almost 60 percent of agricultural non-CO_2 emissions and about 4 percent of all greenhouse gas emissions (USEPA, 2006). Soil carbon effects associated with activities that generate N_2O emissions are not included in the *Global Non-CO_2 Emissions Report* (2006) but are included in this mitigation analysis.

S.3 CH_4 Emissions from Rice Cultivation

CH_4 emissions from rice cultivation are estimated to be the third largest source of global agricultural non-CO_2 emissions. In 2000, rice CH_4 emissions were estimated to be 30,169 Gg or 634 $MtCO_2eq$, and are projected to increase 22 percent by 2020 to 36,958 Gg or 776 $MtCO_2eq$ (a 29 percent increase relative to 1990). These emissions accounted for 11 percent of global agricultural non-CO_2 emissions in 2000. In the United States, less than 2 percent of agricultural non-CO_2 emissions come from rice systems. N_2O and soil carbon effects associated with rice cultivation are not included in the *Global Non-CO_2 Emissions Report* (2006) (because IPCC default emissions factor guidelines were not available) but are included in the baseline and mitigation options used in this analysis.

S.4 CH_4 and N_2O Emissions from Other Agricultural Sources

Both CH_4 and N_2O are produced from the open burning of biomass for agricultural purposes, primarily land clearing for nutrient management. These emissions sources include savanna burning, residue burning, and open burning from forest clearing. Though reported in the *Global Non-CO_2 Emissions Report* (2006), these agricultural emissions are excluded from the mitigation analysis. In 2000, joint CH_4 and N_2O emissions were estimated to be 730 $MtCO_2eq$ and are expected to remain level through 2020. Emissions from other agricultural sources are responsible for about 10 percent of global agricultural non-CO_2 emissions.

Appendix T: IMPACT Commodity Price Data

Table T-1: Region-Specific Input Prices

Region	Agricultural Labor (2000$/year)			Fertilizer (2000$/metric ton)		
	2000	2010	2020	2000	2010	2020
United States	$32,239	$39,299	$47,906	$672	$707	$743
EC-15	$31,941	$38,936	$47,463	$844	$888	$933
Japan	$20,352	$24,808	$30,241	$1,168	$1,227	$1,290
Australia	$18,892	$23,029	$28,072	$739	$776	$816
Other Developed	$29,530	$35,997	$43,880	$579	$609	$640
E Europe	$806	$982	$1,198	$414	$435	$458
Cenasia	$806	$982	$1,198	$414	$435	$458
Rest Former USSR	$806	$982	$1,198	$414	$435	$458
Mexico	$3,305	$4,028	$4,910	$477	$502	$527
Brazil	$3,184	$3,881	$4,732	$729	$766	$805
Argentina	$3,184	$3,881	$4,732	$783	$823	$865
Colombia	$3,184	$3,881	$4,732	$576	$606	$637
O L America	$3,184	$3,881	$4,732	$735	$772	$812
Nigeria	$351	$428	$522	$305	$321	$337
N SSAfrica	$303	$369	$450	$606	$637	$670
C&W SSAfrica	$303	$369	$450	$794	$835	$878
S SSAfrica	$303	$369	$450	$579	$609	$640
E SSAfrica	$278	$339	$413	$794	$835	$878
Egypt	$6,448	$7,860	$9,581	$342	$359	$378
Turkey	$967	$1,179	$1,437	$325	$342	$359
O WANA	$6,448	$7,860	$9,581	$619	$651	$684
India	$266	$324	$395	$227	$239	$251
Pakistan	$794	$968	$1,180	$396	$417	$438
Bangladesh	$552	$673	$820	$288	$302	$318
O S Asia	$512	$624	$761	$345	$363	$382
Indonesia	$842	$1,027	$1,252	$297	$312	$328
Thailand	$1,008	$1,229	$1,498	$552	$581	$610
Malaysia	$1,556	$1,896	$2,312	$507	$533	$560
Philippines	$794	$968	$1,180	$572	$601	$632
Viet Nam	$386	$471	$574	$479	$503	$529
Myanmar	$887	$1,081	$1,317	$552	$581	$610
O SE Asia	$882	$1,075	$1,311	$663	$697	$732
China	$335	$408	$497	$490	$515	$541
S Korea	$9,232	$11,254	$13,719	$615	$646	$679
O E Asia	$335	$408	$497	$490	$515	$541
ROW	$503	$614	$748	$672	$707	$743

Table T-2: Global Commodity Output Prices

Commodity	2000	2010	2020
Beef	$1,712	$1,604	$1,474
Pork	$2,221	$2,121	$1,943
Sheep and goat	$2,839	$2,629	$2,382
Poultry	$665	$611	$563
Eggs	$1,174	$1,114	$1,013
Milk	$307	$282	$246
Wheat	$106	$101	$91
Rice	$209	$197	$163
Maize	$72	$71	$67
O coarse grains	$69	$60	$55
Potato	$183	$123	$129
Sweet potatoes and yams	$235	$54	$49
Cassava.	$57	$45	$34
Soybean	$212	$195	$190
Meals	$166	$181	$169
Oils	$527	$437	$338

Appendix U: Detailed Data Tables

Table U-1: Baseline Emissions from Livestock Management ($MtCO_2eq$)

Region	2000	2010	2020
Africa	271.4	332.3	395.2
Annex I	**704.4**	**718.4**	**748.4**
Australia/New Zealand	91.3	92.6	94.0
Brazil	221.7	262.5	297.3
Canada	28.0	34.6	42.7
China	312.9	392.5	470.4
CIS	37.8	38.4	39.0
Eastern Europe	47.8	53.6	57.6
EU-15	222.1	202.9	202.3
India	223.8	260.4	286.3
Japan	19.7	20.8	21.8
Korea, Republic	5.6	6.6	7.7
Latin America/Caribbean	184.9	217.2	246.1
Mexico	42.8	50.1	57.2
Middle East	25.7	34.3	38.2
Non-EU Europe	6.3	6.2	6.1
Non-OECD Annex I	**111.3**	**130.7**	**150.2**
OECD	**641.6**	**644.4**	**663.0**
OPEC	97.8	124.3	146.1
Russian Federation	65.9	78.4	91.0
South & SE Asia	186.9	231.9	276.2
Turkey	30.8	33.4	35.4
Ukraine	22.7	26.8	31.7
United States	171.5	172.6	170.9
World Total	2,219.7	2,548.2	2,866.9

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-2: Baseline Emissions from Rice Cultivation ($MtCO_2eq$)

Region	2000	2010	2020
Africa	—	—	—
Annex I	**45.1**	**27.8**	**27.4**
Australia/New Zealand	—	—	—
Brazil	—	—	—
Canada	—	—	—
China	384.9	300.8	302.1
CIS	—	—	—
Eastern Europe	—	—	—
EU-15	—	—	—
India	127.1	111.4	121.5
Japan	45.1	27.8	27.4
Korea, Republic	18.1	15.1	16.1
Latin America/Caribbean	—	—	—
Mexico	—	—	—
Middle East	—	—	—
Non-EU Europe	—	—	—
Non-OECD Annex I	**—**	**—**	**—**
OECD	**63.3**	**42.9**	**43.5**
OPEC	**425.3**	**221.2**	**218.6**
Russian Federation	—	—	—
South & SE Asia	928.8	583.4	594.5
Turkey	—	—	—
Ukraine	—	—	—
United States	—	—	—
World Total	1,504.1	1,038.4	1,061.6

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-3: Baseline Emissions from Agricultural Soil Management ($MtCO_2eq$)

Region	2000	2010	2020
Africa	29.2	32.1	36.0
Annex I	**508.1**	**483.7**	**521.3**
Australia/New Zealand	12.5	16.6	17.4
Brazil	27.5	29.5	29.9
Canada	—	—	—
China	91.1	97.4	103.9
CIS	42.0	33.8	37.7
Eastern Europe	38.2	39.1	41.1
EU-15	91.0	92.7	100.6
India	65.7	69.1	72.7
Japan	0.4	0.4	0.5
Korea, Republic	0.2	0.2	0.2
Latin America/Caribbean	24.8	29.2	32.0
Mexico	14.3	16.4	17.3
Middle East	11.1	12.7	14.4
Non-EU Europe	14.4	15.4	17.4
Non-OECD Annex I	**171.0**	**122.9**	**124.3**
OECD	**313.3**	**338.2**	**373.4**
OPEC	**15.4**	**17.3**	**19.1**
Russian Federation	171.0	122.9	124.3
South & SE Asia	25.1	26.3	27.6
Turkey	14.0	17.8	20.4
Ukraine	—	—	—
United States	166.6	178.7	199.6
World Total	838.9	830.4	893.0

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

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 U-4: Baseline Emissions from Agriculture ($MtCO_2eq$)

Region	2000	2010	2020
Africa	300.6	364.4	431.1
Annex I	**1,257.6**	**1,229.9**	**1,297.1**
Australia/New Zealand	103.9	109.2	111.3
Brazil	249.2	292.1	327.2
Canada	28.0	34.6	42.7
China	788.9	790.7	876.4
CIS	79.8	72.2	76.7
Eastern Europe	86.0	92.7	98.7
EU-15	313.1	295.6	302.9
India	416.5	440.9	480.5
Japan	65.2	49.0	49.7
Korea, Republic	23.9	21.9	24.0
Latin America/Caribbean	209.7	246.3	278.2
Mexico	57.1	66.5	74.5
Middle East	36.9	47.0	52.6
Non-EU Europe	20.6	21.6	23.5
Non-OECD Annex I	**282.3**	**253.6**	**274.5**
OECD	**1,018.1**	**1,025.5**	**1,079.9**
OPEC	**538.5**	**362.9**	**383.9**
Russian Federation	237.0	201.3	215.3
South & SE Asia	1,140.7	841.6	898.2
Turkey	44.8	51.2	55.8
Ukraine	22.7	26.8	31.7
United States	338.1	351.3	370.5
World Total	4,562.6	4,417.0	4,821.5

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Note: These emissions reflect the baseline emissions used in calculating agricultural mitigation.

Table U-5. Percentage Mitigation ($MtCO_2eq$) by Carbon Price Level for Livestock Management

	2010					2020				
Region	**$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%
Canada	3.2%	3.2%	7.5%	9.2%	9.3%	2.9%	3.7%	7.5%	8.3%	8.5%
China	2.0%	3.4%	3.7%	3.7%	4.1%	2.0%	3.4%	3.7%	3.7%	4.0%
CIS	2.9%	2.9%	2.9%	3.2%	3.3%	3.1%	3.1%	3.1%	3.4%	3.7%
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%
Korea, Republic	4.0%	4.0%	4.0%	7.1%	7.1%	3.6%	3.6%	3.6%	6.6%	6.6%
Latin America/ Caribbean	3.5%	4.3%	4.7%	4.7%	5.8%	3.2%	4.3%	4.7%	4.7%	5.8%
Mexico	3.3%	3.3%	3.3%	3.4%	3.4%	3.3%	3.3%	3.3%	3.4%	3.4%
Middle East	0.5%	0.5%	1.2%	1.3%	1.3%	0.5%	1.1%	1.3%	1.3%	1.3%
Non-EU Europe	3.1%	3.1%	7.1%	8.7%	8.8%	3.4%	4.4%	8.9%	9.8%	10.0%
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%**
OPEC	**1.6%**	**3.3%**	**4.1%**	**4.2%**	**4.8%**	**1.3%**	**2.2%**	**3.8%**	**4.1%**	**4.8%**
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%
Turkey	7.1%	7.1%	7.1%	7.1%	7.1%	7.0%	7.0%	7.0%	7.0%	7.0%
Ukraine	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.9%
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%

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-6. Percentage Mitigation ($MtCO_2eq$) by Carbon Price Level for Agricultural Soil Management

	2010					2020				
Region	**$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%
Canada	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
China	6.4%	6.4%	6.7%	10.1%	12.7%	5.8%	6.3%	7.3%	10.5%	12.5%
CIS	10.7%	11.9%	11.9%	11.9%	11.9%	10.3%	10.6%	10.6%	10.6%	10.6%
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%
Korea, Republic	13.9%	16.1%	16.1%	16.1%	16.5%	13.3%	15.6%	15.6%	15.6%	15.6%
Latin America/ Caribbean	15.1%	16.3%	18.1%	22.0%	24.9%	13.7%	14.6%	15.4%	20.2%	23.0%
Mexico	10.8%	14.3%	23.4%	23.4%	23.4%	10.5%	23.2%	23.2%	23.2%	23.2%
Middle East	5.1%	5.3%	7.3%	7.9%	8.7%	4.7%	4.9%	4.9%	5.4%	6.2%
Non-EU Europe	31.6%	48.6%	48.6%	48.6%	48.7%	32.1%	47.4%	47.4%	47.4%	47.4%
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%**
OPEC	**5.5%**	**5.9%**	**7.4%**	**10.4%**	**11.0%**	**5.1%**	**5.4%**	**5.5%**	**8.1%**	**8.7%**
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%
Turkey	5.2%	5.2%	11.3%	11.3%	11.3%	4.9%	4.9%	5.3%	10.4%	12.7%
Ukraine	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
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%

CIS = Commonwealth of Independent States; EU-15 = European Union; NA = Data unavailable; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-7. Percentage Mitigation ($MtCO_2eq$) by Carbon Price Level for Rice Cultivation

	2010					2020				
Region	**$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
Canada	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%
CIS	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
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%
Korea, Republic	8.4%	11.0%	26.0%	26.0%	26.0%	9.6%	26.1%	26.1%	26.1%	26.1%
Latin America/ Caribbean	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mexico	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Middle East	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Non-EU Europe	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%**
OPEC	**11.7%**	**16.4%**	**16.4%**	**16.4%**	**16.4%**	**12.3%**	**17.4%**	**17.4%**	**17.4%**	**17.4%**
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%
Turkey	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ukraine	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
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%

CIS = Commonwealth of Independent States; EU-15 = European Union; NA = Data unavailable; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-8. Percentage Total Agricultural Mitigation ($MtCO_2eq$) by Carbon Price Level

	2010					2020				
Region	**$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%
Canada	3.2%	3.2%	7.5%	9.2%	9.3%	2.9%	3.7%	7.5%	8.3%	8.5%
China	7.8%	14.2%	14.1%	14.5%	15.0%	6.3%	11.6%	12.1%	12.5%	12.9%
CIS	6.5%	7.1%	7.1%	7.3%	7.3%	6.6%	6.8%	6.8%	7.0%	7.1%
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%
Korea, Republic	7.1%	8.9%	19.3%	20.2%	20.2%	7.3%	17.7%	17.7%	18.7%	18.7%
Latin America/ Caribbean	4.9%	5.7%	6.3%	6.8%	8.1%	4.4%	5.5%	6.0%	6.5%	7.8%
Mexico	5.2%	6.0%	8.3%	8.3%	8.3%	5.0%	8.0%	8.0%	8.0%	8.0%
Middle East	1.7%	1.8%	2.9%	3.1%	3.3%	1.6%	2.1%	2.3%	2.4%	2.7%
Non-EU Europe	23.4%	35.5%	36.7%	37.2%	37.2%	24.6%	36.1%	37.3%	37.6%	37.6%
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%**
OPEC	**8.0%**	**11.4%**	**11.7%**	**11.9%**	**12.2%**	**7.8%**	**11.1%**	**11.7%**	**12.0%**	**12.3%**
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%
Turkey	6.4%	6.4%	8.5%	8.5%	8.5%	6.3%	6.3%	6.4%	8.3%	9.1%
Ukraine	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.9%
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%

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-9. Mitigation ($MtCO_2eq$) by Carbon Price Level for Livestock Management

	2010					2020				
Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	2.3	7.1	8.8	11.7	11.9	2.2	8.2	10.1	13.9	14.1
Annex I	**36.2**	**49.3**	**72.7**	**81.4**	**90.1**	**37.0**	**55.0**	**77.0**	**89.3**	**95.2**
Australia/New Zealand	3.8	4.0	6.3	6.9	7.8	3.9	4.3	6.8	7.2	8.1
Brazil	7.7	11.7	13.0	13.0	17.0	8.7	13.3	14.7	14.7	19.3
Canada	1.1	1.1	2.6	3.2	3.2	1.2	1.6	3.2	3.5	3.6
China	8.0	13.3	14.6	14.6	15.9	9.5	15.8	17.3	17.3	18.9
CIS	1.1	1.1	1.1	1.2	1.3	1.2	1.2	1.2	1.3	1.4
Eastern Europe	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	2.0
EU-15	12.8	20.5	26.5	26.5	34.2	12.9	20.8	24.7	30.7	34.6
India	3.1	5.6	6.6	6.6	6.6	3.4	7.3	7.3	7.3	7.3
Japan	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0
Korea, Republic	0.3	0.3	0.3	0.5	0.5	0.3	0.3	0.3	0.5	0.5
Latin America/ Caribbean	7.6	9.4	10.3	10.3	12.6	7.8	10.6	11.6	11.6	14.3
Mexico	1.7	1.7	1.7	1.7	1.7	1.9	1.9	1.9	1.9	1.9
Middle East	0.2	0.2	0.4	0.4	0.4	0.2	0.4	0.5	0.5	0.5
Non-EU Europe	0.2	0.2	0.4	0.5	0.5	0.2	0.3	0.5	0.6	0.6
Non-OECD Annex I	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.7**	**3.7**	**3.7**	**3.7**	**4.5**
OECD	**34.8**	**47.9**	**71.3**	**80.2**	**88.9**	**35.4**	**53.4**	**75.4**	**87.9**	**93.0**
OPEC	**2.0**	**4.1**	**5.1**	**5.2**	**6.0**	**1.9**	**3.3**	**5.5**	**6.0**	**7.0**
Russian Federation	1.9	1.9	1.9	1.9	1.9	2.2	2.2	2.2	2.2	2.7
South & SE Asia	9.1	12.4	14.2	14.3	15.4	9.7	12.6	16.5	16.7	18.1
Turkey	2.4	2.4	2.4	2.4	2.4	2.5	2.5	2.5	2.5	2.5
Ukraine	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.9
United States	11.1	16.2	29.7	37.0	37.0	10.8	20.2	33.9	39.2	39.2
World Total	77.2	111.9	143.7	155.8	173.3	81.9	126.7	158.5	175.0	191.4

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-10. Mitigation ($MtCO_2eq$) by Carbon Price Level for Agricultural Soil Management

	2010					2020				
Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	3.6	4.1	4.5	4.6	4.7	3.8	4.9	4.9	5.0	5.1
Annex I	**99.7**	**112.2**	**143.6**	**146.3**	**149.4**	**102.2**	**108.1**	**126.2**	**149.0**	**152.0**
Australia/New Zealand	3.5	3.5	4.1	5.7	5.7	3.8	3.8	4.5	6.3	6.3
Brazil	1.6	1.6	3.9	3.9	3.9	1.4	1.4	3.7	3.7	3.7
Canada	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
China	6.2	6.2	6.6	9.8	12.4	6.0	6.5	7.6	11.0	13.0
CIS	3.6	4.0	4.0	4.0	4.0	3.9	4.0	4.0	4.0	4.0
Eastern Europe	5.7	7.4	8.2	8.4	9.4	5.6	7.3	8.6	8.6	8.6
EU-15	11.0	11.8	12.1	12.7	14.4	10.9	10.9	11.5	11.8	13.9
India	4.3	7.9	7.9	8.3	8.6	4.2	8.4	8.4	8.4	8.4
Japan	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Korea, Republic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latin America/ Caribbean	4.4	4.7	5.3	6.4	7.3	4.4	4.7	4.9	6.5	7.4
Mexico	1.8	2.3	3.8	3.8	3.8	1.8	4.0	4.0	4.0	4.0
Middle East	0.6	0.7	0.9	1.0	1.1	0.7	0.7	0.7	0.8	0.9
Non-EU Europe	4.9	7.5	7.5	7.5	7.5	5.6	8.2	8.2	8.2	8.2
Non-OECD Annex I	**34.8**	**34.8**	**58.7**	**58.9**	**59.3**	**34.9**	**34.9**	**39.4**	**59.1**	**59.5**
OECD	**61.0**	**72.4**	**80.6**	**82.9**	**84.5**	**63.6**	**70.0**	**82.3**	**85.4**	**87.9**
OPEC	**1.0**	**1.0**	**1.3**	**1.8**	**1.9**	**1.0**	**1.0**	**1.0**	**1.6**	**1.7**
Russian Federation	34.8	34.8	58.7	58.9	59.3	34.9	34.9	39.4	59.1	59.5
South & SE Asia	2.1	2.2	2.5	3.5	3.8	2.3	2.3	3.0	3.9	3.9
Turkey	0.9	0.9	2.0	2.0	2.0	1.0	1.0	1.1	2.1	2.6
Ukraine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United States	38.8	46.3	50.9	50.9	50.9	40.4	42.0	52.9	52.9	52.9
World Total	127.9	145.9	183.1	191.8	198.9	130.6	145.0	167.5	196.2	202.4

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-11. Mitigation ($MtCO_2eq$) by Carbon Price Level for Rice Cultivation

	2010					2020				
Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Annex I	**0.4**	**6.7**	**6.7**	**6.7**	**6.7**	**0.5**	**6.8**	**6.8**	**6.8**	**6.8**
Australia/New Zealand	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0
Canada	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
China	47.4	92.5	90.2	90.2	90.2	39.5	79.0	81.3	81.3	81.3
CIS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eastern Europe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EU-15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
India	–0.3	29.4	27.5	27.5	27.5	–0.3	28.8	28.8	28.8	28.8
Japan	0.4	6.7	6.7	6.7	6.7	0.5	6.8	6.8	6.8	6.8
Korea, Republic	1.3	1.7	3.9	3.9	3.9	1.4	3.9	3.9	3.9	3.9
Latin America/ Caribbean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mexico	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-EU Europe	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-OECD Annex I	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
OECD	**1.7**	**8.4**	**10.6**	**10.6**	**10.6**	**1.9**	**10.7**	**10.7**	**10.7**	**10.7**
OPEC	**25.9**	**36.3**	**36.3**	**36.3**	**36.3**	**27.2**	**38.5**	**38.5**	**38.5**	**38.5**
Russian Federation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South & SE Asia	60.6	97.1	98.3	120.5	129.8	70.5	111.3	111.3	132.5	132.7
Turkey	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ukraine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United States	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
World Total	109.5	227.3	226.6	248.9	258.2	111.6	229.8	232.1	253.3	253.5

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-12. Total Agricultural Mitigation ($MtCO_2eq$) by Carbon Price Level

	2010					2020				
Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	5.9	11.2	13.2	16.4	16.6	6.0	13.1	15.0	18.9	19.2
Annex I	**136.3**	**168.1**	**223.0**	**234.4**	**246.1**	**139.7**	**169.9**	**210.0**	**245.0**	**254.0**
Australia/New Zealand	7.3	7.5	10.4	12.7	13.6	7.7	8.1	11.3	13.5	14.4
Brazil	9.2	13.3	16.9	16.9	21.0	10.0	14.6	18.4	18.4	23.0
Canada	1.1	1.1	2.6	3.2	3.2	1.2	1.6	3.2	3.5	3.6
China	61.7	112.1	111.3	114.6	118.5	55.1	101.4	106.2	109.6	113.2
CIS	4.7	5.1	5.1	5.2	5.3	5.1	5.2	5.2	5.3	5.4
Eastern Europe	7.2	8.8	9.7	9.9	10.9	7.1	8.9	10.1	10.1	10.6
EU-15	23.9	32.3	38.6	39.2	48.6	23.8	31.7	36.2	42.5	48.5
India	7.1	42.8	42.0	42.5	42.7	7.3	44.5	44.5	44.5	44.5
Japan	1.3	7.6	7.7	7.7	7.7	1.4	7.7	7.7	7.8	7.8
Korea, Republic	1.6	2.0	4.2	4.4	4.4	1.7	4.2	4.2	4.5	4.5
Latin America/ Caribbean	12.0	14.1	15.5	16.7	19.8	12.2	15.3	16.6	18.1	21.6
Mexico	3.5	4.0	5.5	5.5	5.5	3.7	5.9	5.9	5.9	5.9
Middle East	0.8	0.8	1.3	1.4	1.5	0.9	1.1	1.2	1.3	1.4
Non-EU Europe	5.1	7.7	7.9	8.0	8.0	5.8	8.5	8.8	8.8	8.8
Non-OECD Annex I	**38.0**	**38.0**	**61.9**	**62.1**	**62.5**	**38.5**	**38.5**	**43.0**	**62.7**	**64.1**
OECD	**97.5**	**128.6**	**162.5**	**173.7**	**184.0**	**100.9**	**134.1**	**168.4**	**184.0**	**191.6**
OPEC	**28.9**	**41.3**	**42.6**	**43.2**	**44.1**	**30.1**	**42.8**	**45.0**	**46.0**	**47.1**
Russian Federation	36.7	36.7	60.6	60.8	61.2	37.0	37.0	41.6	61.3	62.2
South & SE Asia	71.9	111.7	115.0	138.4	149.0	82.5	126.2	130.9	153.0	154.7
Turkey	3.3	3.3	4.4	4.4	4.4	3.5	3.5	3.6	4.6	5.1
Ukraine	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.9
United States	49.8	62.5	80.6	88.0	88.0	51.3	62.2	86.7	92.1	92.1
World Total	314.6	485.1	553.3	596.5	630.4	324.1	501.5	558.0	624.5	647.4

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-13. Agricultural Mitigation of CH_4 in Terms of $MtCO_2eq$

	2010					2020				
Region	**$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	**4.9%**	**7.5%**	**10.6%**	**11.8%**	**13.0%**	**4.8%**	**8.0%**	**10.8%**	**12.4%**	**13.1%**
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%
Canada	3.2%	3.2%	7.5%	9.2%	9.3%	2.9%	3.7%	7.5%	8.3%	8.5%
China	8.0%	15.3%	15.1%	15.1%	15.3%	6.3%	12.3%	12.8%	12.8%	13.0%
CIS	2.9%	2.9%	2.9%	3.2%	3.3%	3.1%	3.1%	3.1%	3.4%	3.7%
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	0.8%	9.4%	9.2%	9.2%	9.2%	0.8%	8.9%	8.9%	8.9%	8.9%
Japan	2.6%	15.5%	15.7%	15.7%	15.7%	2.7%	15.6%	15.6%	15.7%	15.7%
Korea, Republic	7.1%	8.9%	19.3%	20.2%	20.2%	7.2%	17.7%	17.7%	18.7%	18.7%
Latin America/ Caribbean	3.5%	4.3%	4.7%	4.7%	5.8%	3.2%	4.3%	4.7%	4.7%	5.8%
Mexico	3.3%	3.3%	3.3%	3.4%	3.4%	3.3%	3.3%	3.3%	3.4%	3.4%
Middle East	0.5%	0.5%	1.2%	1.3%	1.3%	0.5%	1.1%	1.3%	1.3%	1.3%
Non-EU Europe	3.1%	3.1%	7.1%	8.7%	8.8%	3.4%	4.4%	8.9%	9.8%	10.0%
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	**5.3%**	**8.2%**	**11.9%**	**13.2%**	**14.5%**	**5.3%**	**9.1%**	**12.2%**	**14.0%**	**14.7%**
OPEC	**8.1%**	**11.7%**	**12.0%**	**12.0%**	**12.2%**	**8.0%**	**11.4%**	**12.1%**	**12.2%**	**12.5%**
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	8.6%	13.4%	13.8%	16.5%	17.8%	9.2%	14.2%	14.7%	17.1%	17.3%
Turkey	7.1%	7.1%	7.1%	7.1%	7.1%	7.0%	7.0%	7.0%	7.0%	7.0%
Ukraine	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.9%
United States	6.4%	9.4%	17.2%	21.4%	21.4%	6.3%	11.8%	19.8%	23.0%	23.0%
World Total	5.2%	9.5%	10.3%	11.3%	12.0%	4.9%	9.1%	9.9%	10.9%	11.3%

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-14. Agricultural Mitigation of CH_4 in Terms of $MtCO_2eq$

Region	2010 $0	2010 $15	2010 $30	2010 $45	2010 $60	2020 $0	2020 $15	2020 $30	2020 $45	2020 $60
Africa	2.3	7.1	8.8	11.7	11.9	2.2	8.2	10.1	13.9	14.1
Annex I	**36.7**	**55.9**	**79.4**	**88.1**	**96.8**	**37.5**	**61.8**	**83.7**	**96.0**	**102.0**
Australia/New Zealand	3.8	4.0	6.3	6.9	7.8	3.9	4.3	6.8	7.2	8.1
Brazil	7.7	11.7	13.0	13.0	17.0	8.7	13.3	14.7	14.7	19.3
Canada	1.1	1.1	2.6	3.2	3.2	1.2	1.6	3.2	3.5	3.6
China	55.5	105.8	104.8	104.8	106.1	49.0	94.8	98.6	98.6	100.1
CIS	1.1	1.1	1.1	1.2	1.3	1.2	1.2	1.2	1.3	1.4
Eastern Europe	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	2.0
EU-15	12.8	20.5	26.5	26.5	34.2	12.9	20.8	24.7	30.7	34.6
India	2.9	34.9	34.2	34.2	34.2	3.1	36.1	36.1	36.1	36.1
Japan	1.3	7.5	7.6	7.6	7.6	1.3	7.7	7.7	7.7	7.7
Korea, Republic	1.5	1.9	4.2	4.4	4.4	1.7	4.2	4.2	4.4	4.4
Latin America/ Caribbean	7.6	9.4	10.3	10.3	12.6	7.8	10.6	11.6	11.6	14.3
Mexico	1.7	1.7	1.7	1.7	1.7	1.9	1.9	1.9	1.9	1.9
Middle East	0.2	0.2	0.4	0.4	0.4	0.2	0.4	0.5	0.5	0.5
Non-EU Europe	0.2	0.2	0.4	0.5	0.5	0.2	0.3	0.5	0.6	0.6
Non-OECD Annex I	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**	**3.7**	**3.7**	**3.7**	**3.7**	**4.5**
OECD	**36.6**	**56.2**	**81.9**	**90.9**	**99.5**	**37.3**	**64.1**	**86.1**	**98.6**	**103.7**
OPEC	**28.0**	**40.3**	**41.3**	**41.4**	**42.2**	**29.1**	**41.7**	**44.0**	**44.5**	**45.4**
Russian Federation	1.9	1.9	1.9	1.9	1.9	2.2	2.2	2.2	2.2	2.7
South & SE Asia	69.7	109.5	112.5	134.9	145.2	80.2	123.9	127.8	149.1	150.7
Turkey	2.4	2.4	2.4	2.4	2.4	2.5	2.5	2.5	2.5	2.5
Ukraine	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.9
United States	11.1	16.2	29.7	37.0	37.0	10.8	20.2	33.9	39.2	39.2
World Total	186.7	339.2	370.3	404.7	431.5	193.5	356.5	390.6	428.3	444.9

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-15. Agricultural Mitigation of N_2O in Terms of $MtCO_2eq$

	2010					2020				
Region	**$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%
Canada	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
China	6.4%	6.4%	6.7%	10.1%	12.7%	5.8%	6.3%	7.3%	10.5%	12.5%
CIS	10.7%	11.9%	11.9%	11.9%	11.9%	10.3%	10.6%	10.6%	10.6%	10.6%
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%
Korea, Republic	13.9%	16.1%	16.1%	16.1%	16.5%	13.3%	15.6%	15.6%	15.6%	15.6%
Latin America/ Caribbean	15.1%	16.3%	18.1%	22.0%	24.9%	13.7%	14.6%	15.4%	20.2%	23.0%
Mexico	10.8%	14.3%	23.4%	23.4%	23.4%	10.5%	23.2%	23.2%	23.2%	23.2%
Middle East	5.1%	5.3%	7.3%	7.9%	8.7%	4.7%	4.9%	4.9%	5.4%	6.2%
Non-EU Europe	31.6%	48.6%	48.6%	48.6%	48.7%	32.1%	47.4%	47.4%	47.4%	47.4%
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%**
OPEC	**5.5%**	**5.9%**	**7.4%**	**10.4%**	**11.0%**	**5.1%**	**5.4%**	**5.5%**	**8.1%**	**8.7%**
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%
Turkey	5.2%	5.2%	11.3%	11.3%	11.3%	4.9%	4.9%	5.3%	10.4%	12.7%
Ukraine	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
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%

CIS = Commonwealth of Independent States; EU-15 = European Union; NA = Data unavailable; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.

Table U-16. Agricultural Mitigation of N_2O in Terms of $MtCO_2eq$

	2010					2020				
Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	3.6	4.1	4.5	4.6	4.7	3.8	4.9	4.9	5.0	5.1
Annex I	**99.7**	**112.2**	**143.6**	**146.3**	**149.4**	**102.2**	**108.1**	**126.2**	**149.0**	**152.0**
Australia/New Zealand	3.5	3.5	4.1	5.7	5.7	3.8	3.8	4.5	6.3	6.3
Brazil	1.6	1.6	3.9	3.9	3.9	1.4	1.4	3.7	3.7	3.7
Canada	—	—	—	—	—	—	—	—	—	—
China	6.2	6.2	6.6	9.8	12.4	6.0	6.5	7.6	11.0	13.0
CIS	3.6	4.0	4.0	4.0	4.0	3.9	4.0	4.0	4.0	4.0
Eastern Europe	5.7	7.4	8.2	8.4	9.4	5.6	7.3	8.6	8.6	8.6
EU-15	11.0	11.8	12.1	12.7	14.4	10.9	10.9	11.5	11.8	13.9
India	4.3	7.9	7.9	8.3	8.6	4.2	8.4	8.4	8.4	8.4
Japan	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Korea, Republic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latin America/Caribbean	4.4	4.7	5.3	6.4	7.3	4.4	4.7	4.9	6.5	7.4
Mexico	1.8	2.3	3.8	3.8	3.8	1.8	4.0	4.0	4.0	4.0
Middle East	0.6	0.7	0.9	1.0	1.1	0.7	0.7	0.7	0.8	0.9
Non-EU Europe	4.9	7.5	7.5	7.5	7.5	5.6	8.2	8.2	8.2	8.2
Non-OECD Annex I	**34.8**	**34.8**	**58.7**	**58.9**	**59.3**	**34.9**	**34.9**	**39.4**	**59.1**	**59.5**
OECD	**61.0**	**72.4**	**80.6**	**82.9**	**84.5**	**63.6**	**70.0**	**82.3**	**85.4**	**87.9**
OPEC	**1.0**	**1.0**	**1.3**	**1.8**	**1.9**	**1.0**	**1.0**	**1.0**	**1.6**	**1.7**
Russian Federation	34.8	34.8	58.7	58.9	59.3	34.9	34.9	39.4	59.1	59.5
South & SE Asia	2.1	2.2	2.5	3.5	3.8	2.3	2.3	3.0	3.9	3.9
Turkey	0.9	0.9	2.0	2.0	2.0	1.0	1.0	1.1	2.1	2.6
Ukraine	—	—	—	—	—	—	—	—	—	—
United States	38.8	46.3	50.9	50.9	50.9	40.4	42.0	52.9	52.9	52.9
World Total	127.9	145.9	183.1	191.8	198.9	130.6	145.0	167.5	196.2	202.4

CIS = Commonwealth of Independent States; EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; OPEC = Organization of the Petroleum Exporting Countries.