United States Environmental Protection Agency
Office of Atmospheric Programs (6207J)
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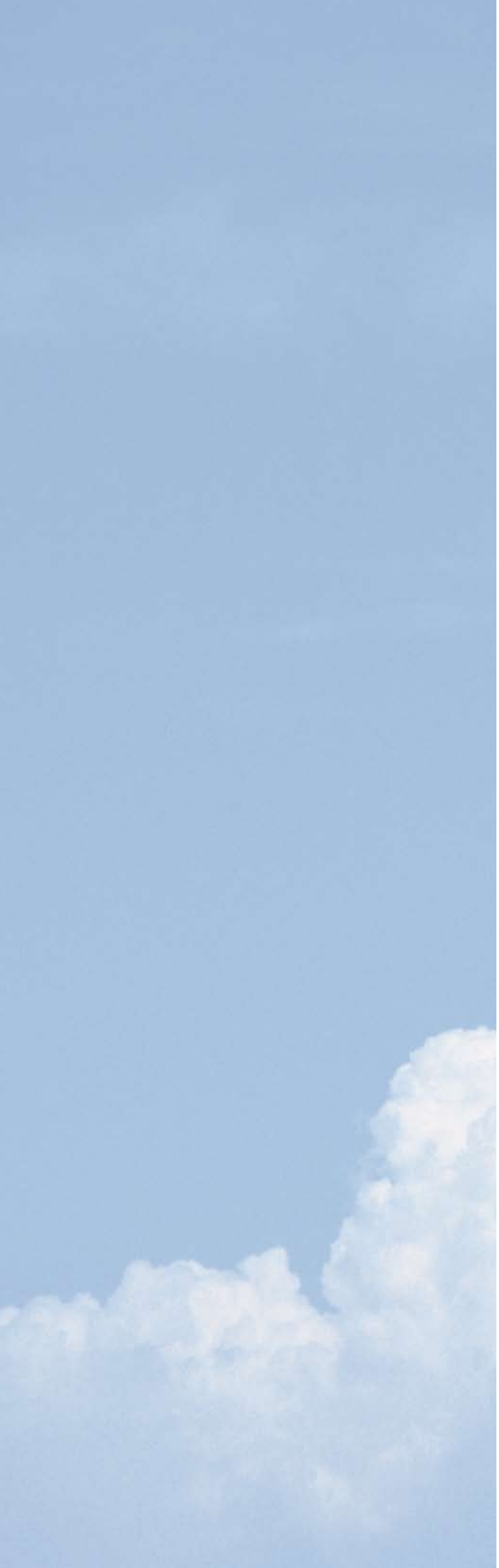
Global Mitigation of Non-CO_2 Greenhouse Gases



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Executive Summary

The mitigation of noncarbon dioxide (non-CO_2) greenhouse gas emissions can be a relatively inexpensive supplement to CO_2-only mitigation strategies. The non-CO_2 gases include methane (CH_4), nitrous oxide (N_2O), and a number of high global warming potential (high-GWP) or fluorinated gases. These gases trap more heat within the atmosphere than CO_2 per unit weight. Approximately 30 percent of the anthropogenic greenhouse effect since preindustrial times can be attributed to these non-CO_2 greenhouse gases (Intergovernmental Panel for Climate Change [IPCC], 2001b); approximately 24 percent of GWP-weighted greenhouse gas emissions in the year 2000 are comprised of the non-CO_2 greenhouse gases (de la Chesnaye et al., in press; U.S. Environmental Protection Agency [USEPA], 2006).

Given the important role that mitigation of non-CO_2 greenhouse gases can play in climate strategies, there is a clear need for an improved understanding of the mitigation potential for non-CO_2 sources, as well as for the incorporation of non-CO_2 greenhouse gas mitigation in climate economic analyses. This report provides a comprehensive global analysis and resulting data set of marginal abatement curves (MACs) that illustrate the abatement potential of non-CO_2 greenhouse gases by sector and by region. This assessment of mitigation potential is unique because it is comprehensive across all non-CO_2 gases, across all emitting sectors of the economy, and across all regions of the world.

The analysis in this report is the latest refinement of the methodology on mitigation of various non-CO_2 gases, which has been underway since 1999. A significant contribution to the climate change mitigation literature is Stanford University's Energy Modeling Forum Working Group 21 (EMF-21), which focused on mitigation of multiple greenhouse gases and resulted in the publication of a special issue of the *Energy Journal* (see Weyant and de la Chesnaye, in press). The specific non-CO_2 mitigation papers in the EMF-21 study include energy- and industry-related CH_4 and N_2O (Delhotal et al., in press); agricultural-related CH_4 and N_2O (DeAngelo et al., in press); and industry-related fluorinated gases (Ottinger et al., in press). Much of the original work comes from three previous USEPA studies for the United States (2006, 2001, 1999) and a study conducted by the European Commission (EC) (2001) that evaluated technologies and costs of CH_4 abatement for European Union (EU) members from 1990 to 2010. These studies provided estimates of potential CH_4 and N_2O emissions reductions from major emitting sectors and quantified costs and benefits of these reductions.

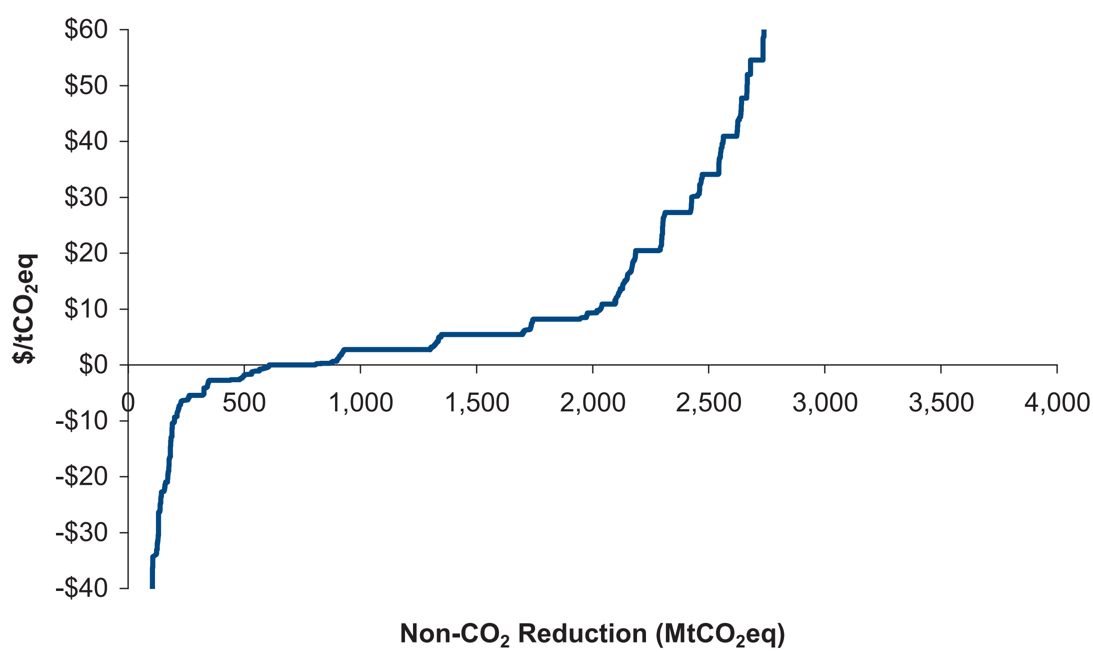
Building on the baseline non-CO_2 emissions projections from the USEPA's *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020* (2006), this analysis applies mitigation options to the emissions baseline in each sector. Across all the emitting greenhouse gas sectors, for each mitigation option, the technical abatement potential and cost are calculated. The MACs are determined by the series of breakeven price calculations for the suite of available options for each sector and region. Each point along the curve indicates the abatement potential given the economically feasible mitigation technologies at a given breakeven price. This report makes no explicit assumption about policies that would be required to facilitate and generate adoption of mitigation options. Therefore, this report provides estimates of technical mitigation potential.

The result of these efforts is a set of MACs that allow for improved understanding of the mitigation potential for non-CO_2 sources, as well as inclusion of non-CO_2 greenhouse gas mitigation in economic modeling. The MAC data sets can be downloaded in spreadsheet format from the USEPA Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

Highlights of this analysis include the following:

Mitigation of Non-CO_2 Gases Can Play an Important Role in Climate Strategies. Worldwide, the potential for "no-regret" non-CO_2 greenhouse gas abatement is significant. Figure ES-1 shows the global total aggregate MAC for the year 2020. Without a price signal (i.e., at \$0/tCO_2eq), the global mitigation potential is greater than 600 million metric tons of CO_2 equivalent (MtCO_2eq), or 5 percent of the baseline emissions (refer to Section I.3.3 of this report for a more detailed explanation of unrealized mitigation potential in the MACs). As the breakeven price rises, the mitigation potential grows. Significant mitigation opportunities could be realized in the lower range of breakeven prices. The global mitigation potential at a price of \$10/tCO_2eq is greater than 2,000 MtCO_2eq, or 15 percent of the baseline emissions, and greater than 2,185 MtCO_2eq or 17 percent of the baseline emissions at \$20/tCO_2eq. In the higher range of breakeven prices, the MAC becomes steeper, and less mitigation potential exists for each additional increase in price.

Figure ES-1: Global Total Aggregate MAC for Non-CO_2 Greenhouse Gases in 2020



Globally, the Sectors with the Greatest Potential for Mitigation of Non-CO_2 Greenhouse Gases are the Energy and Agriculture Sectors. Figure ES-2 shows the global MACs by economic sector in 2020. At a breakeven price of \$30/tCO_2eq, the potential for reduction of non-CO_2 greenhouse gases is nearly 1,000 MtCO_2eq in the energy sector, and approximately 600 MtCO_2eq in the agriculture sector. While less than that of the energy and agriculture sectors, mitigation potential in the waste and industrial processes sectors can play an important role, particularly in the absence of a carbon price incentive.

Methane Mitigation has the Largest Potential across All the Non-CO_2 Greenhouse Gases. Figure ES-3 shows the global MACs by greenhouse gas type for 2020. At or below \$0/tCO_2eq, the potential for CH_4 mitigation is approximately 500 MtCO_2eq. The potential for reducing CH_4 emissions grows to nearly 1,800 MtCO_2eq as the breakeven price rises from \$0 to \$30/tCO_2eq. While less than that of CH_4, N_2O and high-GWP gases exhibit significant mitigation potential at or below \$0/tCO_2eq.

Figure ES-2: Global 2020 MACs for Non-CO_2 Greenhouse Gases by Major Sector

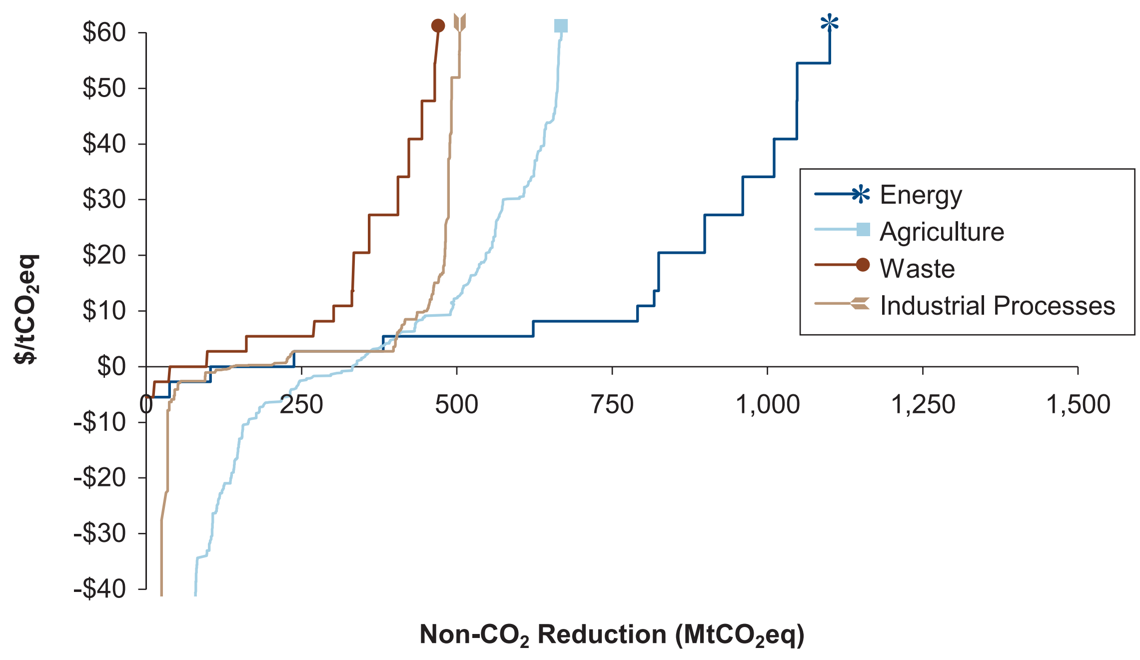
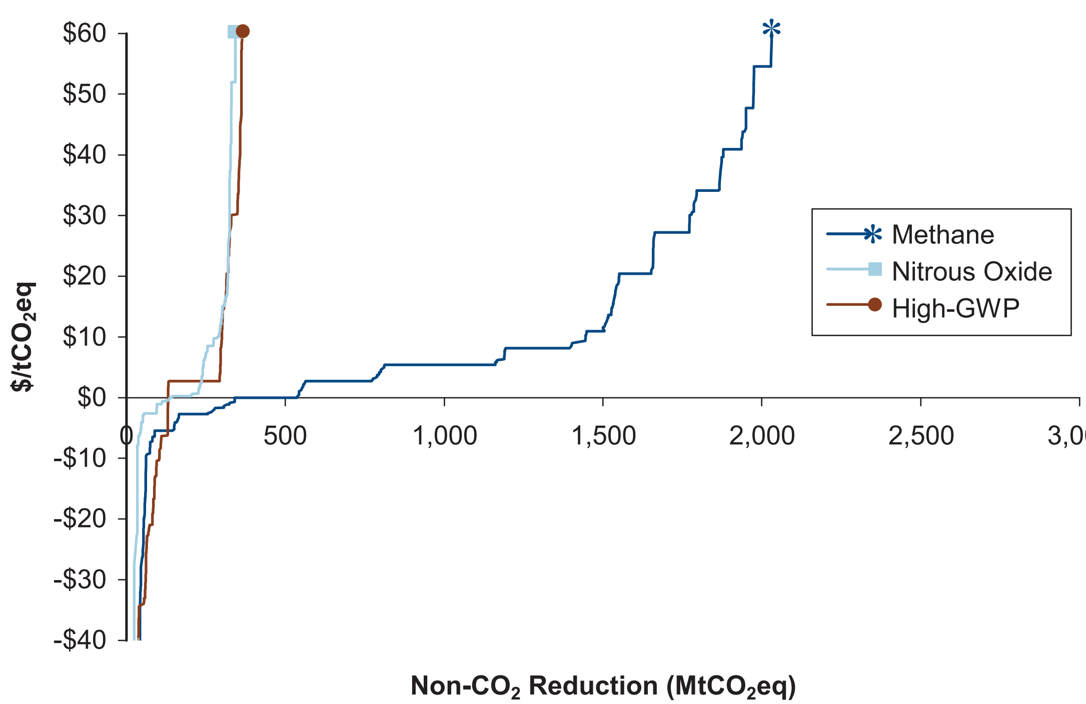
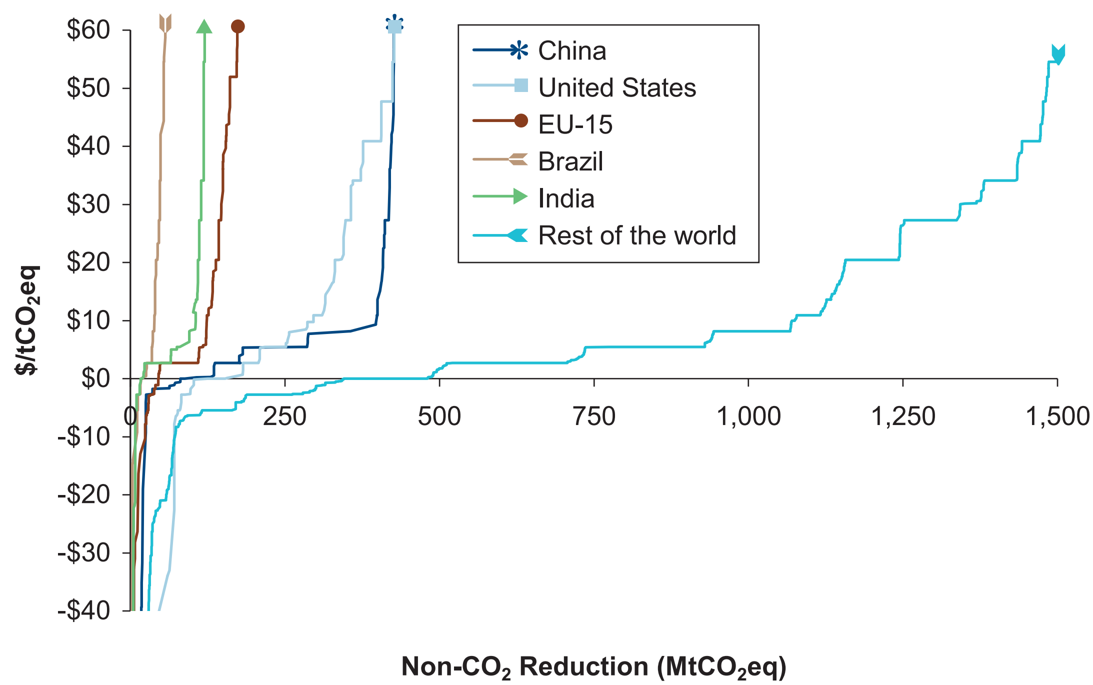


Figure ES-3: Global 2020 MACs by Non-CO_2 Greenhouse Gas Type



Major Emitting Regions of the World Offer Large Potential Mitigation Opportunities. Figure ES-4 shows the global MACs by region for 2020. China, the United States, EU, India, and Brazil are the countries or regions that emit the most non-CO_2 greenhouse gases. As the largest emitters, they also offer important mitigation opportunities. These regions show significant mitigation potential in the lower range of breakeven prices, with the MACs getting steeper in the higher range of breakeven prices as each additional ton of emissions becomes more expensive to reduce.

Figure ES-4: Global 2020 MACs for Non-CO_2 Greenhouse Gases by Major Emitting Regions



The aggregate MACs by economic sector, greenhouse gas type, and region highlight the importance of including non-CO_2 greenhouse gases in the analysis of multigas climate strategies. The MACs illustrate that a significant portion of this emissions reduction potential can be realized at zero or low carbon prices. The mitigation potential in each economic sector is examined in greater detail in this report.

IV. Industrial Processes

This section presents international emissions baselines and marginal abatement curves (MACs) for 11 industrial sources. Each chapter in this section addresses one of these sources. These sources include nitrous oxide (N_2O) emitted during nitric and adipic acid production; fluorinated gases that are used as substitutes for ozone-depleting substances (ODSs); and high–global warming potential (GWP) gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from several industrial sources. MAC data are presented in both percentage reduction and absolute reduction terms relative to the baseline emissions. These data can be downloaded in spreadsheet format from the U.S. Environmental Protection Agency (USEPA) Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

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

Nitric Oxide

IV.1 N_2O Emissions from Nitric and Adipic Acid Production

Fluorinated Gases Used as Substitutes for ODSs

IV.2 HFC Emissions from Refrigeration and Air-Conditioning

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

IV.4 HFC Emissions from Foams

IV.5 HFC Emissions from Aerosols

IV.6 HFC Emissions from Fire Extinguishing

High-GWP Gases from Industrial Processes

IV.7 PFC Emissions from Aluminum Production

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

IV.9 PFC and SF_6 Emissions from Semiconductor Manufacturing

IV.10 SF_6 Emissions from Electric Power Systems

IV.11 SF_6 Emissions from Magnesium (Mg) Production

IV. Industrial Processes Overview

This section presents international emission baselines and MACs for twelve sources of various greenhouse gases, including N_2O, HFCs, PFCs, and SF_6. These sources include production of nitric and adipic acid, which emit N_2O; production of aluminum, magnesium, semiconductors, and HCFC-22, which emit PFCs, SF_6, and HFCs; and use of electrical equipment in electric power systems, which emits SF_6. In addition to the industrial sectors, this section also includes emissions estimates and MACs for fluorinated gases (generally HFCs) that are used as substitutes for ODSs.

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

Table: Global and Regional Emissions Reduction Commitments

Industry	Global Industry Association, Region, or Country	Percentage of World Production/Emissions in 2003	Goal
Semiconductor manufacturing	World Semiconductor Council	85%	Reduce fluorinated emissions to 90% of 1995 level by 2010
Mg production	International Magnesium Association	80% of the magnesium industry is outside of China; about 80% of global SF_6 emissions	Phaseout SF_6 use by 2011
Aluminum production	International Aluminum Institute	70% (but goal applies to entire industry)	Reduce PFCs/ton of aluminum by 80% relative to 1990 levels by 2010
Electrical equipment (use)	EU-25+3, Japan, and United States	40% of use emissions	Country-specific reductions from 2003 totaling 2.5 $MtCO_2eq$, or 15% of these countries' 2003 emissions from use
HCFC-22	China, India, Korea, and Mexico	65% of emissions	CDM projects totaling 55 $MtCO_2eq$, or 63% of these countries' 2010 emissions

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

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

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

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

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

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

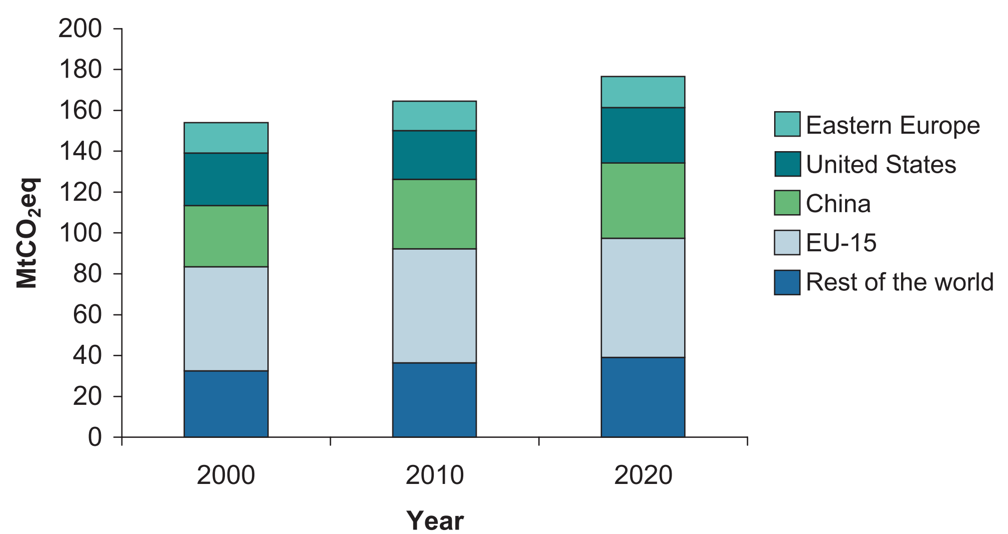
Detailed discussions of the methodology used to develop the baselines for each source can be found in the USEPA (2006) report *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020.*

IV.1 N_2O Emissions from Nitric and Adipic Acid Production

Worldwide N_2O emissions from industrial sources account for more than 154 million metric tons of carbon dioxide (CO_2) equivalent ($MtCO_2eq$) (USEPA, 2006). The USEPA estimates that emissions from nitric and adipic acid production combined contributed approximately 5 percent of total global N_2O emissions in 2000 (USEPA, 2003). Nitric acid production accounts for 67 percent of N_2O emissions from industrial production, and adipic acid accounts for the remaining 33 percent (USEPA, 2003).

Eastern Europe, the United States, China, and the European Union (EU-15) combined account for 79 percent of total N_2O emissions from industrial production (Figure 1-1). The Intergovernmental Panel on Climate Change (IPCC) reports that the number of nitric acid production plants worldwide is estimated at 250 to 600. The United States is the primary producer of adipic acid, with four production sites alone, accounting for approximately 40 percent of total adipic acid production worldwide (USEPA, 2001). Other countries have at most one adipic acid plant (IPCC, 2000).

Figure 1-1: N_2O Emissions from Industrial Production by Country: 2000–2020



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

Global N_2O emissions from industrial production sources are expected to grow by approximately 13 percent between 2005 and 2020 (USEPA, 2006), although the percentage distribution of emissions across countries is projected to remain relatively unchanged.

IV.1.1 Introduction

The two major sources of anthropogenic N_2O emissions from industry are production of nitric and adipic acid. These dicarboxylic acids produce N_2O as a by-product of the production process. N_2O is then emitted in the waste gas stream (USEPA, 2001).

IV.1.1.1 Nitric Acid

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

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

IV.1.1.2 Adipic Acid

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

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

IV.1.2 Baseline Emissions Estimates

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

IV.1.2.1 Activity Factors

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

Historical Activity Data

Nitric Acid

Nitric acid production levels closely follow trends in fertilizer consumption, because of nitric acid’s role as a major component in fertilizer production (Mainhardt and Kruger, 2000). Trends in fertilizer production vary widely across different regions of the world. For example, in Western Europe, because of concerns over nutrient runoff, nitrogen-based fertilizer use has been scaled back. However, in regions where agriculture accounts for a larger share of the gross domestic product (GDP), such as Asia, South America, and the Middle East, nitrogen-based fertilizer production capacity is increasing (Mainhardt and Kruger, 2000).

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

Adipic Acid

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

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

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

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

Source: *CW*, 2003.

Projected Activity Data

Nitric Acid

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

Adipic Acid

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

IV.1.2.2 Emissions Factors and Related Assumptions

Nitric Acid

The IPCC reports that N_2O emissions factors for nitric acid production remain relatively uncertain, because of a lack of information on manufacturing processes and emissions controls. The emissions factor is estimated, based on the average amount of N_2O generated per unit of nitric acid produced, combined with the type of technology employed at a plant. The IPCC uses a default range of 2 to 9 kilograms N_2O per ton of nitric acid produced. As a result, emissions factors for nitric acid production plants may vary significantly based on the type of technology employed at the plant. For example, NSCR is very effective at destroying N_2O, whereas alternative technologies such as SCR and extended absorption do not reduce N_2O emissions.

In the United States, a weighted average of 2 kilograms N_2O per ton nitric acid is used for plants using NSCR systems, and 9.5 kilograms N_2O per ton nitric acid is used for plants not equipped with NSCR. Table 1-2 lists the reported emissions factors by IPCC in the *Revised 1996 Reference Manual*.

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

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

Source: IPCC, 1996.

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

The IPCC points out that potential emissions factors as high as 19.5 kilograms N_2O per ton of nitric acid have been estimated in previous reports. In addition, estimates of 80 percent of the nitric acid plants worldwide do not employ NSCR technology, which makes it more likely that the default range of potential emissions factors provided by the IPCC greatly underestimates the true emissions baselines (Mainhardt and Kruger, 2000).

Adipic Acid

The IPCC provides countries with a default emissions factor of 300 kilograms N_2O per ton of adipic acid produced. This emissions factor assumes that no N_2O control system is in place. This factor was developed using laboratory experiments measuring the reactionary stoichiometry for N_2O generation during the production of adipic acid (Mainhardt and Kruger, 2000). This emissions factor has been supported by some selected measurement at industrial plants. IPCC recommends using plant-specific data for those plants with abatement controls already in place (IPCC, 1996).

IV.1.2.3 Emissions Estimates and Related Assumptions

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

Historical Emissions Estimates

Table 1-3 lists historical N_2O emissions by country. Worldwide N_2O baseline emissions from nitric and adipic acid production decreased by 28 percent between 1990 and 2000. The United Kingdom, Germany, and Canada experienced the largest declines in baselines emissions, with 88 percent, 84 percent, and 77 percent declines, respectively, over the same 10-year period. However, countries such as China, Japan, South Korea, and India saw baseline increases of 54, 29, 25, and 29 percent, respectively.

Table 1-3: N_2O Emissions from Nitric and Adipic Acid Production: 1990–2000 ($MtCO_2eq$)

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

Source: USEPA, 2006.

Projected Emissions Estimates

Table 1-4 lists combined projected N_2O baseline emissions from nitric and adipic acid by country. Worldwide total N_2O emissions from nitric and adipic acid are projected to increase by approximately 16 percent between 2005 and 2020. The United States, South Korea, and Brazil are expected to experience the largest increase in baseline emissions, with 28, 22, and 22 percent, respectively, between 2005 and 2020.

Nitric Acid

Emissions from nitric acid production are expected to increase by 13 percent between 2000 and 2020, because of an expanding market for synthetic fertilizer (see explanatory note 1). Brazil, Mexico, and India are projected to increase their N_2O baseline emissions by 29, 25, and 22 percent, respectively, from nitric acid production (USEPA, 2006).

Table 1-4: Projected N_2O Baseline Emissions from Nitric and Adipic Acid Production: 2005–2020 ($MtCO_2eq$)

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

Source: USEPA, 2006.

Adipic Acid

Emissions from adipic acid production are projected to increase by approximately 40 percent between 2000 and 2020, reflecting increased demand for engineering nylon (see explanatory note 1). Southeast Asia, Brazil, and Mexico are projected to experience 45, 44, and 39 percent increases, respectively, in baseline emissions of N_2O.

IV.1.3 Cost of N_2O Emissions Reductions from Industrial Processes

N_2O emissions can be reduced by optimizing the catalytic oxidation of CH_4 to nitrogen oxide or by decomposing N_2O either during the processing of nitric acid or in the tail gas. Currently, N_2O reduction technologies include extending the reaction process through thermal decomposition in the reaction chamber, reducing N_2O through catalytic reduction in the reaction chamber, using NSCR or SCR in the upstream tail gas expander, or using SCR in the downstream tail gas expander (Smit, Gent, and van den Brink, 2001). Each of the technologies has advantages and disadvantages, including the amount of utilities required to run the technology, downtime at the plant for installation, consumption of the reducing agent, and retrofit limitations at existing plants. Depending on the technology, reduction efficiencies can range from 70 percent to 98 percent and costs can range from \$0.52 to \$9.30 per tCO_2eq for new installations and \$0.86 to \$9.48 per tCO_2eq.

Abatement options for the nitric and adipic acid sectors at the time of the Energy Modeling Forum 21 (EMF-21) analysis were relatively limited. However, more recent innovations have proven effective options for abating N_2O at nitric acid production plants. The data presented in this report use an average reduction and cost of NSCR and SCR technologies. Therefore, the reduction potential is at the high end of the reduction range and the costs are on the lower end of the range. Table 1-5 summarizes cost and emissions reductions for the abatement options included in the EMF-21 analysis (USEPA, 2003).

Table 1-5: Cost of Reducing N_2O Emissions from Industrial Processes

Technology	Breakeven Price ($/tCO2eq)	Emissions Reduction (% from baseline)[a]	Emissions Reduction in 2010 (MtCO2eq)	Emissions Reduction in 2020 (MtCO2eq)
	Assuming a 10% discount rate and 40% tax rate			
Nitric Acid Sector[b]				
Grand Paroisse—high-temperature catalytic reduction method	$2.59	6%	0.05	0.05
BASF—high-temperature catalytic reduction method	$2.36	6%	0.05	0.05
Norsk Hydro—high-temperature catalytic reduction method	$1.99	7%	0.05	0.06
HITK—high-temperature catalytic reduction method	$2.75	7%	0.06	0.06
Krupp uhde—low-temperature catalytic reduction method	$2.92	7%	0.06	0.06
ECN—low-temperature selective catalytic reduction with propane addition	$5.81	7%	0.06	0.06
NSCR[c]	$4.03	6%	0.05	0.05
Adipic Acid Sector[c]				
Thermal destruction	$0.50	50%	0.21	0.24

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

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

[b] Based on 10-year lifetime.

[c] Based on 20-year lifetime.

IV.1.3.1 Nitric Acid: N_2O Abatement Option Opportunities

High-Temperature Catalytic Reduction Method

This N_2O abatement option has several variations developed by different companies, all involving the decomposition of N_2O into nitrogen and oxygen using various catalysts. The average estimated reduction efficiency is approximately 90 percent. Total capital costs for these abatement technologies range from $2.18 to $3.27 per tCO_2eq. Operating and maintenance (O&M) costs vary by country. In the United States, O&M costs can range from $0.14 to $0.22 per tCO_2eq. This abatement option has an average technical lifetime of 10 years, yielding a breakeven price of approximately $0.82 per tCO_2eq.

Low-Temperature Catalytic Reduction Method

Low-temperature catalytic reduction systems work similarly to high-temperature counterparts but do not require heat to decompose the N_2O. This abatement option has a reduction efficiency of 95 percent. Some versions of this abatement option require propane be added to the gas stream before undergoing the reaction process. Total capital cost for this option ranges from $3.27 to $3.55 per tCO_2eq. In the United States, O&M costs range from $0.27 to $1.91 per tCO_2eq. This option has a technical lifetime of 10 years, yielding a breakeven price of approximately $0.82 per tCO_2eq.

Nonselective Catalytic Reduction

NSCR uses a fuel and a catalyst to consume free oxygen in the tail gas, converting nitrogen oxides to elemental nitrogen. The gas from the nitrogen oxides abatement is passed through a gas expander for energy recovery, resulting in a reduction efficiency of 85 percent. The process requires additional fuel and emits CO_2. The total capital cost for this option is \$6.27 per tCO_2eq. In the United States, the O&M cost is estimated at \$0.16 per tCO_2eq. NSCR has a technical lifetime of 20 years, yielding a breakeven price of approximately \$1.90 per tCO_2eq.

IV.1.3.2 Adipic Acid: N_2O Abatement Option Opportunities

Thermal Destruction

Thermal destruction is the destruction of off-gases in boilers using reducing flame burners with premixed CH_4 (or natural gas). The system eliminates between 98 percent and 99 percent of N_2O and operates from 95 percent to 99 percent of the time. Total capital costs for thermal destruction are \$0.38 per tCO_2eq. In the United States, O&M costs are estimated to be approximately \$0.16 per tCO_2eq. This abatement option has a technical lifetime of 20 years, yielding a breakeven price of approximately \$0.27 per tCO_2eq.

IV.1.4 Results

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

IV.1.4.1 Data Tables and Graphs

The nitric and adipic baselines are presented in Tables 1-6 and 1-8. Tables 1-7 and 1-9 present percentage reductions for different carbon prices (\$/tCO_2eq) from the emissions baselines for each sector. Figures 1-2 and 1-3 present these results in graphical form. Significant abatement potential is estimated to exist at \$15 per tCO_2eq. It is estimated that there are no "no-regret" options for N_2O nitric or adipic acid production. At a breakeven price of \$15 per tCO_2eq, the percentage abatement is 89 percent for nitric acid and 96 percent for adipic acid, reflecting the relatively high technical potential and low abatement cost for options in these industrial processes. Technology changes have not been incorporated in the abatement potential for N_2O emissions from industrial processes.

IV.1.4.2 Uncertainties and Limitations

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

Improved Cost Data

Improved documentation of N_2O abatement options and their cost components would improve the analyst's ability to estimate baseline reductions given some estimate of market penetration.

Improved Manufacturing Data for Nitric Acid

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

Table 1-6: Projected N_2O Emissions from Nitric Acid by Region: 2000–2020 ($MtCO_2eq$)

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

Source: USEPA, 2006.
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-7: Percentage Abatement for Nitric Acid for Selected Breakeven Prices ($/$tCO_2eq$): 2010–2020

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

Source: USEPA, 2003. Adapted from Nitric Acid Sector technology tables in Appendix B.
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-8: Projected N_2O Emissions from Adipic Acid by Region: 2000–2020 ($MtCO_2eq$)

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

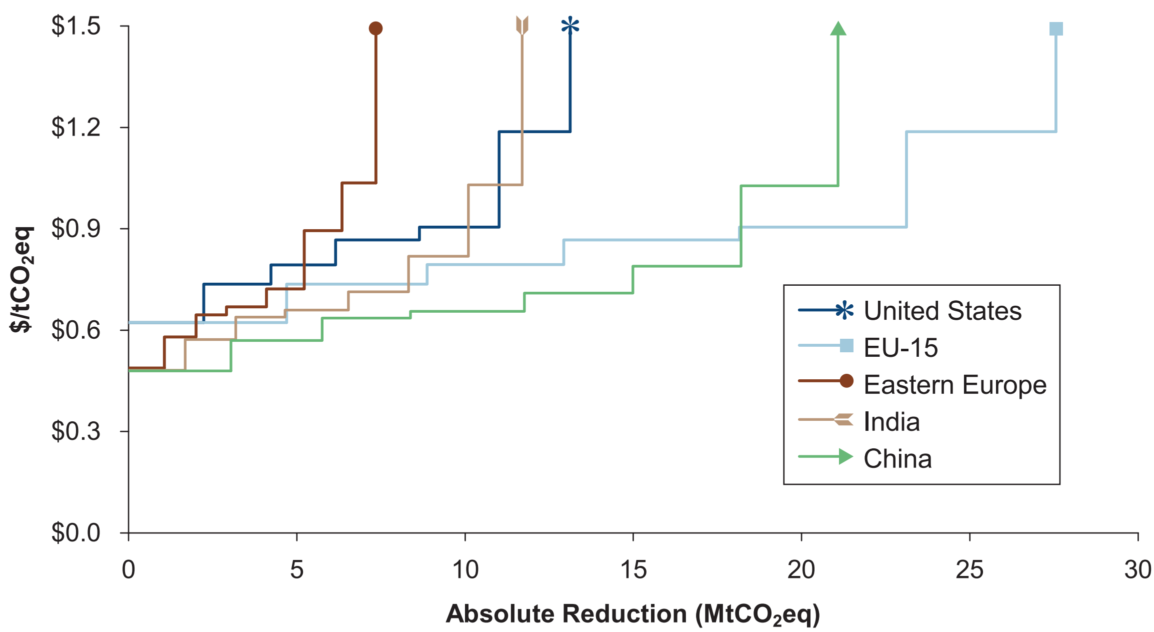
Source: USEPA, 2006.
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-9: Percentage Abatement for Adipic Acid for Selected Breakeven Prices ($/$tCO_2eq$): 2010–2020

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

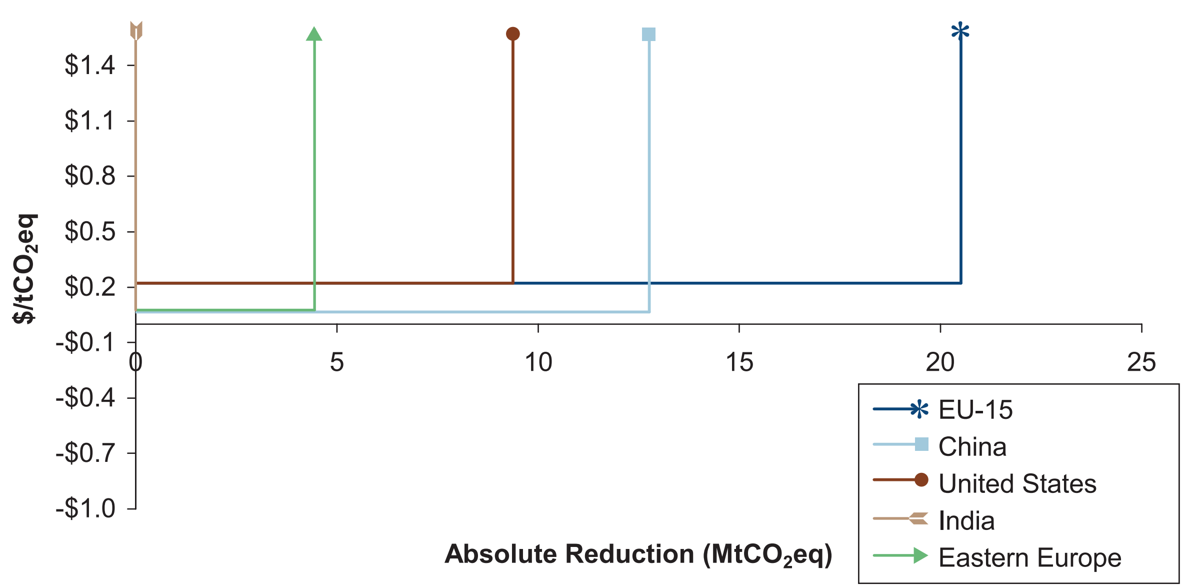
Source: USEPA, 2003. Adapted from Nitric Acid Sector technology tables in Appendix B.
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

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



EU-15 = European Union.

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



EU-15 = European Union.

Improved Emissions Factor Estimates

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

IV.1.5 Summary

Adipic acid producers in the United States have already adopted options to mitigate emissions of N_2O. Nitric and adipic acid production will continue to increase, correlating closely with the world's demand for synthetic fertilizers and nylon. However, certain abatement options may mitigate significant portions of a country's baseline if adopted by producers.

IV.1.6 References

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Explanatory Notes

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

IV.2 HFC Emissions from Refrigeration and Air-Conditioning

IV.2.1 Introduction

A number of HFCs are used in refrigeration and air-conditioning systems and are emitted to the atmosphere during equipment operation and repair. Specifically, emissions occur during product and equipment manufacturing and servicing, and from disposal of equipment and used refrigerant containers. Emissions also occur during equipment operation, as a result of component failure, leaks, and purges. The use of refrigeration and air-conditioning equipment also generates indirect emissions of greenhouse gases (primarily CO_2) from the generation of power required to operate the equipment. In some refrigeration and air-conditioning applications, these indirect emissions outweigh the direct emissions. Therefore, energy efficiency has a major impact on the total greenhouse gas emissions of an application. To the extent possible, both direct and indirect emissions were considered in the refrigeration and air-conditioning analysis; however, options aimed solely at improving energy efficiency rather than abating HFC emissions were not explored in detail. HFCs used in this sector have 100-year GWPs that range from 140 to 11,700; the majority of HFCs used today in the refrigeration and air-conditioning sector have GWPs from 1,300 (i.e., HFC-134a) to 3,300 (i.e., R-507A).

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

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

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

IV.2.1.1 Household Refrigeration

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

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

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

IV.2.1.2 Motor Vehicle Air-Conditioning (MVAC)

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

CFC-12 availability in developing countries and in some developed countries (e.g., the United States) has resulted in its use for servicing older MVACs that were originally manufactured as CFC-12 systems. A variety of refrigerant blends are approved for use in the United States by the USEPA as replacements for CFC-12 in MVACs. However, these blends have not been endorsed by vehicle or system manufacturers. Globally, these blends have captured only a small and declining share of the retrofit market. Some conversions from CFC-12 to pure HCs have been done. However, this is illegal in the United States, and such use in direct expansion systems not designed for a flammable refrigerant can pose safety concerns and is not considered acceptable by much of the global MVAC industry. Climate change concerns associated with the use of HFC-134a resulted in research into and development of other MVAC alternatives. Possible alternatives to HFC-134a systems include transcritical CO_2 systems, hydrocarbons (e.g., in new secondary-loop systems), and HFC-152a systems, all of which are under study and development (SAE, 2003a).

IV.2.1.3 Chillers

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

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

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

IV.2.1.4 Retail Food Refrigeration

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

During the earlier phases of the CFC phaseout in developed countries, the use of HCFC-22 in retail food refrigeration was expanded considerably. Retail food equipment is being retrofitted with HCFC-based blends, although HFC blends are also used as a retrofit refrigerant. The HFC blend R-404A is the preferred refrigerant in new retail food equipment in developed countries, while R-507A is also used extensively in the market (Kuijpers, 2002). In developed countries, both distributed and centralized systems that use HFCs, HCs, ammonia, and CO_2 are being developed (both with and without secondary loops) (Kuijpers, 2002).

IV.2.1.5 Cold Storage Warehouses

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

IV.2.1.6 Refrigerated Transport

The refrigerated transport end-use includes refrigerated ship holds, truck trailers, railway freight cars, refrigerated rigid vans/trucks, and other shipping containers. Although charge sizes vary greatly, the average charge sizes are relatively small (7 to 8 kilograms). The expected lifetime of a refrigerated transport system is 12 years. Trailers, railway cars, and shipping containers using CFC-substitute refrigerants are commonly charged with HFC-134a, R-404A, and HCFC-22 (UNEP, 1999a). Ship holds, on the other hand, rely on HCFC-22 (UNEP, 1999a) and ammonia. In addition to HFC-134a, R-404A can be used in new equipment. Existing equipment can be retrofitted with R-401A, R-402A, R-404A, R-507A, and other refrigerants. In addition, refrigerated transport equipment includes systems that operate based on the evaporation and expansion of liquid CO_2 or nitrogen.

IV.2.1.7 Industrial Process Refrigeration

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

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

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

IV.2.2 Baseline Emissions Estimates

IV.2.2.1 Emissions Estimating Methodology

Description of Methodology

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

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

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

Emissions Equations

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

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

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

where

Es = Emissions from equipment serviced. Emissions in year j from normal leakage and servicing of equipment.

l_a = Annual leakage rate. Average annual leakage rate during normal equipment operation, expressed as a percentage of total chemical charge.

l_s = Service leakage rate. Average annual leakage from equipment servicing, expressed as a percentage of total chemical charge.

Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment in a given year, by weight.

j = Year of emissions.

i = Counter. From 1 to lifetime (k).

k = Lifetime. The average lifetime of the equipment.

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

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

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

where

Ed = Emissions from equipment disposed. Emissions in year j from the disposal of equipment.

Qc = Quantity of chemical in new equipment. Total amount of a specific chemical used to charge new equipment one lifetime (k) ago, by weight.

rm = Chemical remaining. Amount of chemical remaining in equipment at the time of disposal, expressed as a percentage of total chemical charge.

rc = Chemical recovery rate. Amount of chemical that is recovered just prior to disposal, expressed as a percentage of chemical remaining at disposal (rm).

j = Year of emissions.

i = Counter. From 1 to lifetime (k).

k = Lifetime. The average lifetime of the equipment.

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

$$E_j = Es_j + Ed_j \tag{2.3}$$

where

E = Total emissions. Emissions from refrigeration and air-conditioning equipment in year j.

Es = Emissions from equipment serviced. Emissions in a given year from normal leakage and servicing (recharging) of equipment.

Ed = Emissions from equipment disposed. Emissions in a given year from the disposal of equipment.

j = Year of emissions.

Regional Variations and Adjustments

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

- **Adjustment for Regulation (EC) No 2037/2000.** Countries in the EU-15 were assumed to be in full compliance with Regulation (EC) No 2037/2000, which stipulates that no new refrigeration and air-conditioning equipment should be manufactured with HCFCs, as of January 1, 2002.[2] The European Commission (EC) regulation also bans the use of HCFCs for servicing equipment after January 1, 2015. Compliance with these regulations will likely lead to increased use of HFCs to replace HCFCs. These changes were assumed to correspond to increased emissions of 20 percent in 2005, 15 percent in 2010, and 15 percent in 2020, relative to what the EU-15 baseline otherwise would be. These relative emissions increases were determined by running a Vintaging Model scenario where the uses of HCFCs were assumed to comply with the regulation. No adjustments for Regulation (EC) No 2037/2000 were made to the 10 countries that joined the EU in March 2004, as this analysis was conducted prior to this date.

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

- **Recovery and Recycling Adjustments.** For developing (i.e., non-Annex I) countries, countries with economies in transition (CEITs), and Turkey, the emissions were increased by approximately 20 percent over initial estimates to reflect the assumed low levels of recovery and recycling of refrigerants from small end-uses (i.e., MVACs, commercial and residential air-conditioning, refrigerated transport, and other appliances), relative to the United States. This assumed increase in emissions from lower levels of recovery and recycling was based on an analysis of a variety of scenarios using the Vintaging Model, where emissions were first projected assuming an 80-percent baseline recovery rate to reflect the assumed status quo in developed countries and then projected again assuming a 30-percent baseline recovery rate to reflect the assumed status quo in developing countries. The GWP-weighted emissions in the latter low-recovery scenario were determined to be approximately 20 percent higher than in the former high-recovery scenario (ICF Consulting, 2002a).

- **Market Adjustments.** The baseline assumes that HC and ammonia refrigerants and other non-HFC or low-emitting options will penetrate international markets more than the United States market because of differences in safety standards; greater acceptance of non-HFC choices by industry, end-users, regulators, and insurance companies; and increased public and regulatory scrutiny to reduce HFC emissions. To reflect this penetration, baseline emissions estimates of non-U.S. countries were reduced by the following amounts (Table 2-1).

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

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

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

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

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

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

MVAC Analysis

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

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

	2005	2010	2015	2020
Percent	35.9	27.6	22.6	19.9

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

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

India

India's MVAC fleet estimates were developed based on (1) data on MVAC sales prior to 2004, from SIAM (2005), (2) projected annual growth rates of new vehicle sales, and (3) projected annual growth rates of air-conditioning penetration. Specifically, India's future vehicle fleet growth was assumed to be 8 percent per year,[4] while air-conditioning penetration was assumed to increase linearly to reach 95 percent in 2010.[5] Beyond 2010, it was assumed that air-conditioning penetration will be maintained at 95 percent because vehicle air-conditioning will become standard. The assumed air-conditioning market penetration rates for India are summarized in Table 2-3.

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

	2005	2010	2015	2020
Percent	92.5	95	95	95

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

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

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

China

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

All Other Countries

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

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

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

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

Once the MVAC fleet was estimated by country/region, annual MVAC emissions were calculated assuming annual average leak and service emissions of 10.9 percent.[7] MVAC emissions at disposal were assumed to be 42.5 percent of the original MVAC charge in developed countries and 69 percent in developing countries (as a result of zero recovery assumed).[8] All systems were assumed to use HFC-134a refrigerant in the baseline. The new EC Directive on MVACs[9] was not considered in the baseline estimates, as this directive was not finalized at the time this analysis was conducted.

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

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

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

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

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

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

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

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

IV.2.2.2 Baseline Emissions

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

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

The resulting baseline estimates of HFC emissions are summarized in Table 2-7 and Figure 2-1 in million metric tons of carbon dioxide equivalents ($MtCO_2eq$).

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

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

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

IV.2.3.1 Description and Cost Analysis of Abatement Options

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

Practice Options

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

Alternative Refrigerant Options

- ammonia
- HCs
- CO_2
- other low-GWP refrigerants

[11] TEWI is the combined effects of *direct* greenhouse gas impacts (i.e., chemical emissions) and *indirect* greenhouse gas impacts (i.e., energy-related CO_2 emissions).

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

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

Note: Totals may not sum because of independent rounding.

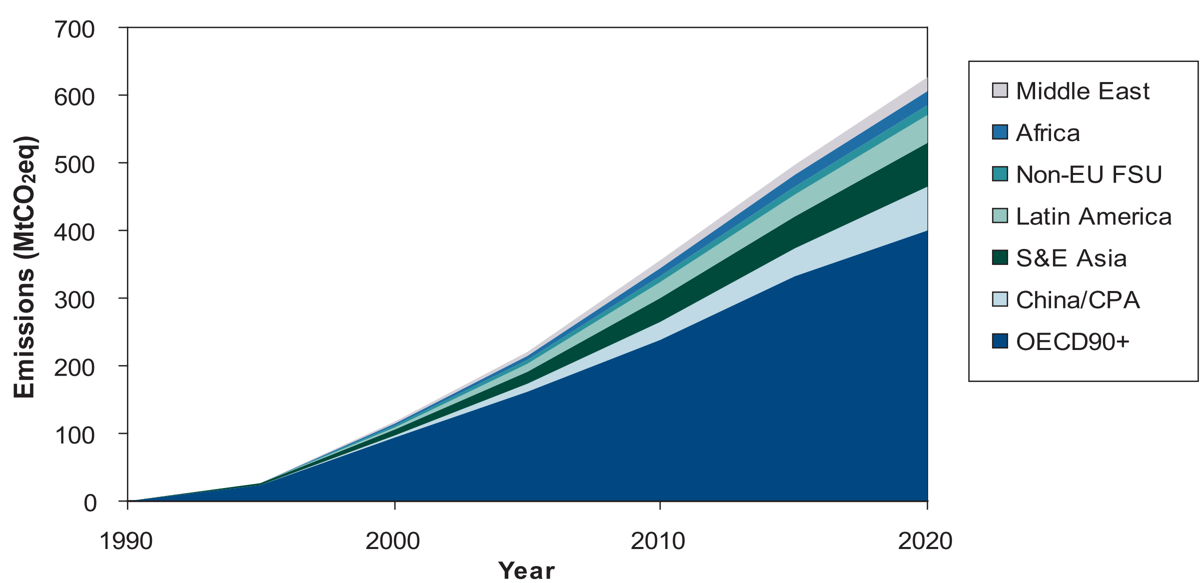
[a] Other appliances include refrigerated appliances, dehumidifiers, and ice makers.

Table 2-7: Total Baseline HFC Emissions from Refrigeration and Air-Conditioning ($MtCO_2eq$)

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

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

Figure 2-1: Baseline HFC Emissions from Refrigeration and Air-Conditioning by Region ($MtCO_2eq$)



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

Technology Options

- distributed systems[12] for stationary commercial refrigeration equipment
- secondary loop systems for stationary equipment, including HFC secondary loop systems and ammonia secondary loop systems
- enhanced HFC-134a systems in MVACs
- HFC-152a refrigerant in MVACs (direct expansion or secondary loop systems)
- CO_2 systems in MVACs
- oil-free compressors
- geothermal (in lieu of air-to-air) cooling systems
- desiccant cooling systems
- absorption systems

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

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

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

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

Option Description	Duration of Emissions Reduction (Years)	Potential Applicability to End-Use Equipment								
		Chillers	Retail Food	Cold Storage Ware-houses	Refrigerated Transport	Industrial Process Refrig-eration	Commercial Air-Conditioning	MVACs	Residential Air-Conditioning	Household Refrigeration and Small Appliances
Practice Options										
Leak repair	5	✓	✓	✓	▪	✓	▪	▪	▪	▪
Refrigerant recovery	1	▪	▪	▪	✓	▪	✓	✓	✓	✓
Proper refrigerant disposal	NA	▪	▪	▪	▪	▪	▪	▪	▪	▪
Technician certification	NA	▪	▪	▪	▪	▪	▪	▪	▪	▪
Alternative Refrigerants										
Ammonia	Lifetime of equipment	▪	✓	✓	▪					▪
HCs	Lifetime of equipment	▪	▪	▪	▪	▪	▪	▪	▪	▪
CO_2	Lifetime of equipment	▪	▪	▪	▪	▪	▪	✓	▪	▪
Other low-GWP refrigerants	Lifetime of equipment	▪	▪	▪	▪	▪	▪	✓	▪	▪
Technology Options										
Distributed systems for stationary commercial refrigeration equipment	Lifetime of equipment		✓	✓						
Secondary loop systems for stationary equipment—HFC primary refrigerant	Lifetime of equipment		✓	✓		▪				
Secondary loops systems for stationary equipment—ammonia primary refrigerant	Lifetime of equipment		✓	✓		▪				
Enhanced HFC-134a systems in MVACs	Lifetime of equipment							✓		
HFC-152a in MVACs (direct expansion or secondary loop)	Lifetime of equipment							✓		
CO_2 in MVACs	Lifetime of equipment							✓		
Oil-free compressors	Lifetime of equipment	▪	▪	▪	▪	▪	▪	▪	▪	▪
Geothermal (in lieu of air-to-air) cooling systems	Lifetime of equipment						▪		▪	
Desiccant cooling systems	Lifetime of equipment	▪					▪		▪	
Absorption systems	Lifetime of equipment	▪					▪		▪	

NA: Not applicable.

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

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

Practice Options

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

Leak Repair for Large Equipment

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

- use of preventive maintenance, including scheduled inspection and repairs;
- monitoring of leaks using stationary leak monitors or other new technologies, such as early warning signals,[13] remote monitoring, and diagnostics;
- use of new, more durable gasket materials that provide tighter seals and absorb less refrigerant;
- augmentation of threaded joints with O-ring seals;
- augmentation or replacement of gaskets and O-rings with adhesive sealants;
- broader use and improvement of brazing techniques rather than threaded or snap fittings (e.g., use of sufficient silver content[14] and use of dry nitrogen or other inert gas to avoid oxidation);
- focus on ensuring accessibility to field joints and use of isolation valves, which allows for greater ease of repair;
- focus on proper securing to reduce vibration fractures in the pipe and connections from the compressor and other moving parts of the system;
- repair or retrofit of high-emitting systems through targeted component upgrades;[15] and
- performance of major modifications to the systems (USEPA, 1997; USEPA, 1998; Calm, 1999).[16]

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

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

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

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

Since the lower-cost leak reduction options represent significant cost savings, this analysis assumes that the leak reductions occur under the baseline. The cost analysis therefore focused only on the more extensive and costly options. This option was assumed to be technically applicable[17] to all equipment with large charge sizes (i.e., chillers, retail food refrigeration, cold storage, and industrial process refrigeration). This analysis assumed that 50 percent of emissions occur as a result of equipment leakage during routine operation, while the other 50 percent of emissions are released during equipment servicing and disposal. Thus, the maximum technical applicability of this option was assumed to be 50 percent of emissions from large equipment (see Table 2-9). Furthermore, this analysis assumed that leak repair can reduce annual system leakage by 40 percent, using an example of a supermarket system that leaks at 25 percent annually but only at 15 percent following repairs. The project lifetime was assumed to be 1 year. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-9. Assumptions on maximum market penetration for each region and year are presented in Table 2-19.

Refrigerant Recovery and Recycling from Small Equipment

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

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

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

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

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

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

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

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

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

This analysis assesses only the recovery of refrigerant from small equipment (i.e., MVACs, refrigerated transport, household and other small appliances, and unitary equipment) above that which is already practiced (e.g., recovery due to regulations in many developed countries or for economic reasons) at service and disposal. It is assumed that recovery from large equipment is already widely practiced in the baseline[19] because of the significant cost savings associated with recovery of large quantities of refrigerant from this equipment. Because emissions reductions and costs vary by scenario and end-use, emissions reductions and costs associated with four recovery scenarios were averaged to obtain one breakeven cost. The four scenarios studied were recovery and recycling of refrigerant from (1) MVACs at service, (2) MVACs at disposal, (3) small appliances at service, and (4) small appliances at disposal.

This analysis assumed that 50 percent of emissions are released during equipment servicing and disposal, while the remaining 50 percent occur as a result of leakage during normal operations. Thus, the technical applicability[20] of this option is 50 percent of emissions from small equipment (see Table 2-10). Furthermore, because in the United States small appliances are considered completely recovered when 90 percent of the refrigerant is removed from units with running compressors, or when 80 percent of the refrigerant is removed from units with nonoperating compressors, this analysis assumed that the reduction efficiency of this option is 85 percent (Contracting Business Interactive, 2003; USEPA, 1993). The project lifetime is assumed to be 1 year. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-10. Recovery from small appliances and MVACs was

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

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

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

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

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

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

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

Proper Refrigerant Disposal

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

Technician Certification and HFC Sales Restriction

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

Alternative Refrigerant Options

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

Ammonia

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

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

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

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

HCs

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

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

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

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

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

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

CO_2

Another option is to use CO_2 as a refrigerant. Prototype CO_2 systems have been developed for numerous types of systems, including MVACs, industrial processing, refrigerated transport, and retail food systems. CO_2 has zero ODP and a GWP of 1, and is claimed by its proponents to be advantageous for use as a refrigerant. However, CO_2 is associated with potential safety risks and other technical and economic disadvantages. Above certain concentrations, exposure to CO_2 may result in adverse health consequences. At very high concentrations, even for short periods of time, CO_2 affects the central nervous system and is toxic. To protect against adverse health effects from workplace exposure, the Occupational Safety and Health Administration (OSHA) recommended an 8-hour time-weighted average exposure limit of 5,000 parts per million (ppm) (ACGIH, 1999). Also, CO_2 systems operate at a high pressure, which presents a potential hazard and may increase the cost of designing and purchasing equipment. In addition, potential loss of operational efficiency and associated increases in energy use and indirect emissions, refrigerant containment issues, long-term reliability, and compressor performance are other potential problems (Environment Canada, 1998).

For this analysis, CO_2 systems were evaluated only as options for MVACs. CO_2 is being investigated for other end-uses but, because research is still in the early stage and there is little information, those end-uses were not explored in this analysis. The MVAC option is described in detail in the section on "Technology Options."

Other Low-GWP Refrigerants

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

Several other low-GWP refrigerants exist. For example, CO_2, discussed above, has a GWP of 1. In addition, HCFC-123 and HCFC-124, which are not considered alternatives to HFCs, have low direct GWPs, but their use is complicated by other factors, including their contribution to stratospheric ozone depletion. While some studies (e.g., Calm, Wuebbles, and Jain, 1999; Wuebbles and Calm, 1997; USEPA, 2002; RTOC, 2003) suggest that the extended use of HCFC-123 in large tonnage chillers may reduce direct GWP-weighted refrigerant emissions, and in some instances may reduce overall greenhouse gas emissions, this option was not examined here because full compliance with the current HCFC phaseout schedule was assumed.

Technology Options

This section presents cost analyses for six alternative technology options, three of which apply to the stationary equipment (distributed systems, HFC secondary loop systems, and ammonia secondary loop systems), and three of which apply to mobile systems (enhanced HFC-134a, HFC-152a, and CO_2). Oil-free compressors, geothermal cooling systems, and desiccant cooling systems are also described qualitatively.

Distributed Systems for Stationary Commercial Refrigeration Equipment

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

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

This technology option is assumed to be applicable to the retail food and cold storage end-uses. The project lifetime is assumed to be 15 years, and the emissions reduction efficiency is calculated to be 90 percent. Regional technical applicability for 2010 and 2020 and reduction efficiency are presented in Table 2-11. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19, expressed as a percentage of emissions from new equipment, and as a percentage of emissions from all equipment (new and existing), respectively. Because the cost analysis for this option does not address the costs to retrofit existing DX systems, this option is assumed to penetrate only new retail food and cold storage installations (i.e., those installed in 2005 or beyond).

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

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

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

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

Secondary Loop Systems for Stationary Equipment

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

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

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

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

HFC Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

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

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

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

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

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

Ammonia Secondary Loop Systems for Stationary Commercial Refrigeration Equipment

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

Because of ammonia's materials capability, toxicity, and flammability, major design modifications would be required for the majority of traditional HFC systems. Furthermore, since different countries have different sets of building codes, fire codes, and other safety standards relating to the use of ammonia in building equipment, some countries (e.g., the United States) would need to revise those codes to allow for the expanded use of ammonia in new equipment types.

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

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

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

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

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

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

Ammonia systems are assumed to penetrate a greater percentage of non-U.S. markets as a result of different safety standards and greater acceptance by industry, end-users, regulators, and insurance companies in those countries. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

Enhanced HFC-134a Systems in MVACs

Various options exist to reduce emissions of HFC-134a in MVACs by reducing charge size, leakage rates, or system efficiency (i.e., reducing system power consumption). Specifically, reducing the volume of the system components, such as the condenser and refrigerant lines, can reduce charge size. Similarly, leakage rates can be lowered and system efficiency improved by using better system components, such as improved system sealing, lower permeation hoses, improved fittings, and higher evaporator temperatures (Lundberg, 2002; Xu and Amin, 2000). Additional savings of indirect emissions can be obtained by improving system efficiency, for example through the use of oil separators and externally controlled swashplate compressors.

Based on the latest science and industry estimates available when this analysis was performed, enhanced HFC-134a systems can reduce baseline direct emissions by 50 percent (SAE, 2003a). This technology is not expected to become commercial until after 2006 (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 2-14.

Table 2-14: Summary of Assumptions for Enhanced HFC-134a Systems for New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency[a]	Technical Applicability[b]	
			2010	2020
United States and Japan	MVACs	50.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

[a] Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems) as a result of reduced leakage.

[b] Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

Acceptance of this substitute would likely vary by region, based on consumer and industry attitudes, economic variables, and availability of competing options. Enhanced HFC-134a systems are expected to become commercially available several years before other alternatives (e.g., CO_2 and HFC-152a). Therefore, this analysis assumes that, initially, enhanced HFC-134a systems will begin to penetrate the markets of developed countries—with the exception of Europe, which is expected to move away from HFC-134a use in MVACs in response to new EC legislation.[21] In developed countries such as the United States, Japan, and Canada, where the industry is resistant to switching from HFC-134a and/or regulations phasing out the use of HFC-134a in MVACs do not exist, this option is assumed to gain the greatest market penetration. In developing countries, capital cost is expected to prevent this option from significantly penetrating the market before 2010; however, given the global market, these systems are expected to gain market share by 2020. The cost analysis for this option does not include any costs associated with retrofitting existing HFC-134a systems. Therefore, this option is assumed to penetrate only new MVACs produced after 2004. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

HFC-152a Refrigerant in MVACs

Replacing HFC-134a refrigerant in MVACs with HFC-152a represents a significant opportunity to reduce GWP-weighted HFC emissions, since the GWP of HFC-152a is 140, 89 percent less than that of HFC-134a, whose GWP is 1,300. HFC-152a is a flammable refrigerant but is less flammable than HCs. HFC-152a can be used in DX and secondary loop MVAC systems. Because there is still great uncertainty associated with the future costs of HFC-152a secondary loop systems for MVACs, this cost analysis only considers the DX option. Likewise, because there is still great uncertainty associated with future costs of improved HFC-152a MVACs, only the conventional DX systems are considered in this cost analysis. However, like the enhanced HFC-134a system discussed above, HFC-152a MVACs will use improved

[21] According to the EC Directive, HFC-134a will be phased out from 2011 onward for new vehicle models and from 2017 for all new vehicles. The directive applies to gases with a GWP higher than 150 (EC, 2004).

system components to further reduce refrigerant leakage rates and increase system efficiency (e.g., externally controlled variable displacement compressors).

In addition to direct emissions reductions associated with a lower GWP, HFC-152a DX systems in MVACs also reduce indirect emissions by improving system efficiency by about 10 percent (SAE, 2003a). This analysis assumes a project lifetime (i.e., MVAC lifetime) of 12 years. Regional technical applicabilities and the reduction efficiency are presented in Table 2-15.

Table 2-15: Summary of Assumptions for HFC-152a DX Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency[a]	Technical Applicability[b]	
			2010	2020
United States and Japan	MVACs	89.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

[a] Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems) as a result of lower GWP.

[b] Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

The use of HFC-152a DX systems in MVACs would not require any significant changes to existing HFC-134a system components apart from a safety mitigation system (e.g., a refrigerant detector and a valve to isolate the remaining charge from the passenger compartment), thereby rendering this option easy to introduce into the market. Furthermore, compared with baseline HFC-134a systems, HFC-152a systems are expected to be more efficient and may operate at reduced refrigerant charges and leakage rates.[22] However, because HFC-152a is a slightly flammable gas, safety systems are needed. Thus, personnel training would be needed to enable the safe and effective recovery and recycling of refrigerant at service and disposal, and additional safety systems to minimize the potential for large leaks into the passenger compartment may be required. New fire-safe service equipment for refrigerant recovery and charging and leak detection may also be required.

While the MVAC industry has demonstrated the use of HFC-152a in prototype DX (and secondary loop) MVAC systems, the technology is still in the research and development phase. HFC-152a systems are expected to become commercially available between 2006 and 2008 (SAE, 2003a). Once available, it is assumed that, initially, HFC-152a systems will gain market share in developed countries, although use in Europe will be tempered by conditions that may favor CO_2 systems. Market penetration in developing countries is expected to lag by about 5 years. Retrofitting HFC-134a systems to HFC-152a systems is not considered technically or economically feasible, because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the system. Thus, costs associated with retrofit were not assessed, and this option is assumed to penetrate only new MVACs produced after 2004. Assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19.

[22] Because these systems are still under development, this cost analysis does not consider the possible reduction in charge and leakage rates, although efficiency improvement predictions based on SAE (2003a) are included.

CO_2 in MVACs

Systems that use CO_2 as the refrigerant in MVACs represent a potential opportunity for emissions reduction. This technology uses a transcritical vapor cycle that differs from conventional MVAC systems and requires innovative design and engineering. The arrangement of components in CO_2 systems is generally consistent with conventional systems; however, a suction line heat exchanger is added and a low side accumulator is used (in place of a high side receiver, which is used in most conventional HFC-134a systems). In addition, the individual system components are designed to reflect the extremely high pressure levels of supercritical CO_2 (about 2,000 pounds per square inch [psig]).

Because CO_2 has a GWP of 1, its use would virtually eliminate the climate impacts of direct refrigerant emissions from MVACs. CO_2 systems perform most efficiently in areas like northern Europe that require air conditioners for cooling and other purposes, but generally have mild ambient temperatures.[23] In addition, heat pump technology for vehicles is under development (VDA, 2003), which may allow CO_2 systems to be used for supplemental heating of the passenger compartment (SAE, 2003a). This technology may be an important function in cars with very efficient engines, where minimal waste heat is available to warm the passenger compartment.

While CO_2 has the advantage of being non-flammable, it is toxic. A short exposure to elevated levels of CO_2 can lead to dizziness, drowsiness, and even death (Lambertsen, 1971; Wong, 1992). In addition, CO_2 system operating pressure is 5 to 10 times that of HFC-134a; therefore, appropriate safety features and new system and component designs are required before this option can be brought to market. Furthermore, an internal heat exchanger, which would further cool the high-temperature CO_2 from the gas cooler and heat the low-temperature CO_2 from the accumulator, would be needed to increase cooling capacity and energy efficiency to acceptable levels. Also, in the event of a large leak, passengers could be exposed to potentially dangerous levels of CO_2; thus, it is assumed that safety systems designed to minimize passenger exposure would be incorporated into the system design.

Several engineering constraints must still be overcome, including those associated with flexible lines, increased system weight, and system leakage and leak detection methods. In addition, because these systems will be designed and built differently than current MVACs and because the high pressure presents additional risks, technicians will need to be trained on how to service and maintain these new systems safely and correctly in order to prevent safety hazards and maintain system performance. New service equipment for refrigerant charging and leak detection may also be required. Moreover, because of the high pressure of these systems and toxicity concerns, MVAC servicing and maintenance would need to be performed by skilled technicians, to prevent safety hazards and maintain system performance.

The efficiency gains associated with CO_2 systems are between 20 and 25 percent (SAE, 2003a). In this cost analysis, 22.5 percent is used for calculation purposes. While there are ongoing efforts to develop improved CO_2 systems for MVACs—which experts predict would exceed this 20 to 25 percent energy efficiency gain—much uncertainty remains regarding the investment costs required to manufacture these systems. Therefore, these improved CO_2 systems are not considered further in this analysis. The assumed project lifetime (i.e., MVAC lifetime) is 12 years. Regional technical applicabilities and the reduction efficiency for the CO_2 option are presented in Table 2-16.

[23] Compared with other refrigerant technologies, prototype CO_2 MVAC systems are not as efficient in warmer climates. The MVAC industry is actively pursuing research and development activities to improve system efficiency in warmer weather conditions (SAE, 2003b).

Table 2-16: Summary of Assumptions for CO_2 Systems in New MVACs

Country/Region	Applicable End-Use Sector(s)	Reduction Efficiency[a]	Technical Applicability[b]	
			2010	2020
United States and Japan	MVACs	100.0%	27.6%	19.9%
Other Annex I countries			42.8%	36.6%
Latin America and Caribbean			13.3%	12.0%
China, Hong Kong, and India			53.0%	65.8%
Other non-Annex I countries, Russian Federation, and Ukraine			3.8%	8.0%

[a] Reduction efficiency applies to all regions and represents the reduction in direct emissions (compared with conventional HFC-134a systems).
[b] Technical applicability is shown as a percentage of total refrigeration and air-conditioning sector emissions and equals the percentage of total refrigeration and air-conditioning sector emissions that are assumed to come from MVACs.

CO_2 systems may be available on the market in the next few years (SAE, 2003a). In light of the new EC directive on MVACs, and because European manufacturers are most aggressively pursuing CO_2, this option is expected to become the dominant market player in this market. In other developed countries, such as the United States, Australia, New Zealand, and Canada, the industry is not developing this technology as aggressively, and it is assumed that this option will not be widely adopted in these markets in the near future. Finally, because of the high capital costs associated with this option (see details below), this technology is also not expected to be adopted in developing countries until later years, assuming a projected global market shift to non-GWP alternatives. The project lifetime is assumed to be 12 years, and assumptions on maximum market penetration for each region and year are presented in Tables 2-18 and 2-19. Retrofitting HFC-134a systems to CO_2 is not considered technically or economically feasible because of the high operating pressures and because it is assumed that additional safety systems to reduce potential passenger exposure must be incorporated into the systems. Thus, costs to retrofit were not assessed, and this option is assumed to penetrate only new MVACs produced after 2004.

Oil-Free Compressors

Oil-free compressors are available for chillers, industrial process applications, and other applications where compressors are used. The elimination of oil in refrigeration and air-conditioning compressors has been achieved through various innovative designs, including the incorporation of magnetic or hybrid ceramic bearings (SKF, 2003; Smithart, 2003). In some systems, oil may decrease heat transfer and reduce operating efficiency; therefore, removing oil may increase the ability to sustain system efficiency over the life of the equipment. This reduction will lower indirect emissions of CO_2 associated with electricity production. Eliminating the use of oil in compressors can reduce the number of equipment components (e.g., oil separators and sealing, fittings, and connections), allowing equipment to be made tighter, resulting in lower leakage rates. In addition, oil-free compressors remove the need for oil changes and the associated refrigerant emissions that may be experienced through the service practices used or from refrigerant dissolved in the oil. However, this potential emissions reduction may be offset by an increased frequency of compressor and bearing inspection or replacement (Digmanese, 2004), although an increasing history of operation may prove that unnecessary. This option was not included in the cost analysis because limited data were available.

Geothermal Cooling Systems

In some locations, geothermal cooling systems for residential and commercial spaces are popular and economically sound as an alternative to conventional air-conditioning systems. Geothermal technology transfers heat between the system and the earth and can provide both space heating and cooling. Though installation costs for geothermal systems are typically 30 percent to 50 percent higher than for conventional systems, annual costs are reduced by 20 percent to 40 percent because of increased energy efficiency. Economic paybacks can accrue in as little as 3 to 5 years. Geothermal systems may save homeowners 20 percent to 50 percent in cooling costs (Geoexchange, 2000; Rawlings, 2000). Because of a lack of cost and market penetration data, this technology is not considered further in this analysis.

Desiccant Cooling Systems

Desiccant cooling is produced by removing moisture from an air stream using a desiccant and then separately cooling the dry air. The desiccant is thermally regenerated, typically by burning natural gas or by capturing excess heat. Desiccant cooling may replace the latent cooling done by some end-uses, such as unitary systems. Integrated desiccant cooling systems that combine a desiccant system with a vapor compression or other cooling system have been successfully installed in some commercial buildings (Fisher, Tomlinson, and Hughes, 1994). However, current designs are used primarily in niche markets that require precisely controlled humidity or low humidity levels, such as hospital operating rooms and certain industrial processes. For desiccant-based systems to be considered widely feasible in the commercial air-conditioning market, improvements in efficiency, cost, size, reliability, and life expectancy must be made (Sand et al., 1997).

Desiccant systems have also been tried in MVAC systems, but were found technically and economically infeasible. These systems require an intermittent source of heat; however, because new automobiles produce very little waste heat, there is not enough heat for a desiccant system to function. Desiccant systems may only be feasible where there is a large heat source, such as a large truck or bus (Environment Canada, 1998). Furthermore, in order for desiccant air-conditioners to become viable options for MVACs, the varying heat source must be controlled during normal driving conditions when vehicle speed is continually changing. Current prototypes are large and heavy, and the systems have not been shown to be cost-effective or durable enough to justify the initial investment (USEPA, 2001a).

Because of the technical barriers and insufficient cost information associated with the feasibility of this option, desiccant cooling systems were not explored further in this analysis.

Absorption Systems

Absorption systems refrigerate or cool using two fluids and some quantity of heat input, rather than using electrical input. Specifically, absorption systems use a secondary fluid or absorbent to circulate the refrigerant (Rafferty, 2003). These systems can be used in residential refrigeration and chiller applications and, potentially, in heat pumps in residential and light commercial applications, as described below.

- **Refrigeration Systems.** In the late 1990s, more than 1 million of an estimated 62 million refrigerators sold annually were thermally activated ammonia or water absorption systems (Sand et al., 1997). The refrigerants used for absorption refrigeration have negligible GWPs. Absorption refrigeration is commonly used in hotel rooms and for recreational vehicles because the process operates quietly and can use bottled gas for energy. Absorption refrigerators are limited in size because of design constraints. Through design improvements, the thermal coefficient of performance (COP) of these refrigerators can be increased by as much as 50 percent from a COP of 0.2 to 0.3 without degrading cooling capacity (Sand et al., 1997). However, the low efficiency of absorption equipment means that the indirect emissions must be carefully analyzed. Inherent design limitations make it unlikely that absorption refrigeration will become a significant replacement for vapor compression refrigerators. Still, absorption refrigeration has great capacity and operating attributes that permit the technology to fill niche markets (Sand et al., 1997).

- **Chillers.** Gas-fired (as opposed to electrically powered) absorption water chillers are sold in the United States and Japan. These systems are used primarily where there is a relatively short cooling season, where electricity costs (especially demand charges) are high, or where fairly high-grade waste heat is available. Although absorption chillers are far less efficient than competitive systems if waste heat is unavailable, the technology is feasible and, under some economic circumstances, compares favorably with vapor compression chillers using fluorocarbon refrigerants. Market success will be determined by factors such as the relative costs of natural gas and electricity, peak load charges, and purchase costs. In addition, absorption chillers currently have higher capital costs than vapor compression equipment, such that significant operating cost savings would be necessary to make their purchase economically competitive.
- **Heat Pumps.** Research and development efforts are attempting to create absorption heat pumps for heating and cooling in residential and light commercial applications. Several years ago in Europe and the United States, generator absorber heat exchange (GAX) ammonia-water absorption heat pumps were being developed and in Japan field test units had been built. Absorption heat pumps could be used to reduce global warming impacts in areas where heating load dominates, although the pumps would have the opposite effect in areas where cooling dominates (Sand et al., 1997).

Because these options are either still under development or are primarily optimal in niche markets, sufficient information was not available to include their costs and reduction potential in this analysis.

IV.2.3.2 Summary of Technical Applicability, Market Penetration, and Costs of Abatement Options

Table 2-19 summarizes the percentage of total refrigeration and air-conditioning sector emissions that may be technically abated by each of the options explored in this analysis, based on the percentage of sector emissions from each end-use (which varies by region), as provided in Table 2-6. Market penetration values for each abatement option were developed for each region, when possible, to best reflect qualitative information available on region-specific realities and possible future action. The commercial refrigeration and MVAC technology options explored in this chapter are assumed to penetrate only new (not existing) equipment, where new equipment is defined as equipment manufactured in 2005 or later. Table 2-18 presents the assumed maximum market penetration for the technology options into equipment manufactured in 2005, 2010, 2015, and 2020. Table 2-19 presents the final maximum penetration into the installed base of equipment, taking into account the percentage of each market that is new (i.e., manufactured in 2005 or beyond) in all preceding years. Values from Table 2-19 are multiplied by technical applicabilities (Table 2-17) and the reduction efficiency to generate the percentage reduction off baseline emissions for each option, as presented in Table 2-20. The text box provided in Section IV. 2.4provides further explanation on how the results (i.e., percentage reduction off baseline emissions) are calculated.

IV.2.4 Results

Emissions reduction potential for abatement options varies by region based on assumed end-use breakouts (provided in Table 2-6) and on qualitative information regarding current and future likelihood of market penetration by region. The percentage reduction from the baseline associated with each abatement option is calculated by multiplying the technical applicability (from Table 2-17) by both the incremental maximum market penetration (from Table 2-18) and the reduction efficiency. For more information on how emissions reductions are calculated for each option, please see the text box below, which presents an illustrative example of the emissions reduction methodology.

Calculating Emissions Reductions for Each Abatement Option

The equation used to derive total emissions reductions off the baseline for each option is as follows:

Emissions Reduction = technical applicability × incremental maximum market penetration (expressed as percentage of entire installed base) × reduction efficiency

The following table provides a sample calculation using the option of leak repair for large equipment in the United States in 2020 as an example.

Sample Calculation of Emissions Reductions: Leak Repair for Large Equipment—United States (2020)

Applicable End-Uses (Table 2-9)	Technical Applicability[a] (Based on Tables 2-6 and 2-9)		Incremental Maximum Market Penetration (Table 2-19)		Reduction Efficiency (Table 2-9)		Percentage Reduction from 2020 Baseline (Table 2-20)
Chillers	1.5 × 50%		5%		40%		0.02
Retail food	39.1 × 50%		5%		40%		0.39
Cold storage	1.4 × 50%		5%		40%		0.01
Industrial process	6.6 × 50%		5%		40%		0.07
Total	48.7 × 50%	×	5%	×	40%	=	0.49[b]

[a] For each country/region, technical applicability varies based on the percentage of sector emissions from applicable end-uses, as provided in Table 2-6. Additionally, for the leak repair and refrigerant recovery and recycling options, only half of the emissions from applicable end-uses (i.e., large end-uses for leak repair and small end-uses for recovery and recycling) are assumed to be abatable; for all other options, 100 percent of emissions from new (post-2004) equipment in applicable end-uses are assumed to be abatable.

[b] Total may not sum due to independent rounding.

Table 2-21 presents a summary of the cost assumptions used for the refrigeration/air-conditioning options presented in the discussions above.

IV.2.4.1 Data Tables and Graphs

Tables 2-22 and 2-23 provide a summary of the potential emissions reductions at various breakeven costs by country/region in 2010 and 2020, respectively. The costs to reduce 1 tCO_2eq are presented at a 10 percent discount rate and 40 percent tax rate. Table 2-24 presents the potential emissions reduction opportunities and associated annualized costs for the world in 2020 ordered by increasing costs per tCO_2eq, using the highest cost in the region. Because many of the options analyzed affect indirect (CO_2 from energy generation) emissions, the net (HFC + CO_2) emissions reduced by each option are presented. The direct (HFC) emissions reduced by the option and a cumulative total of direct emissions reduced, in $MtCO_2eq$ and percentage of the regional refrigeration and air-conditioning baseline, are also presented. Figures 2-2 and 2-3 present MACs for this sector at 10 percent discount rates and 40 percent tax rates in 2010 and 2020, respectively.

Table 2-17: Summary of Technical Applicability of Abatement Options by Region (Percent)[a]

Abatement Option	United States and Japan				China, Hong Kong, and India				Europe, Australia, New Zealand, and All Other Annex I Countries				Latin America and Caribbean				Russian Federation, Ukraine, and All Non-Annex I Countries			
	2005	2010	2015	2005	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Refrigerant recovery from small equipment	26.0	24.3	24.6	25.7	28.1	33.3	37.5	39.6	30.1	29.7	27.6	30.7	17.9	19.2	21.3	23.3	14.0	15.8	19.0	22.1
Leak repair for large equipment	24.0	25.7	25.4	24.3	21.9	16.7	12.5	10.4	19.9	20.3	22.4	19.3	32.1	30.8	28.7	26.7	36.0	34.2	31.0	27.9
Ammonia secondary loop	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
Distributed system	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
HFC secondary loop system	40.2	43.1	42.6	40.6	36.8	28.0	20.9	17.3	33.3	34.1	37.5	32.1	53.8	51.7	48.1	44.5	60.3	57.3	52.1	46.6
Enhanced HFC-134a in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0
HFC-152a in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0
CO_2 in MVACs	35.9	27.6	22.6	19.9	41.3	53.0	62.0	65.8	46.9	42.8	31.8	36.6	14.2	13.3	12.6	12.0	3.8	3.8	5.4	8.0

[a] Expressed as a percentage of total refrigeration and air-conditioning emissions.

Table 2-18: Assumed Regional Market Penetration of Abatement Options into Newly Manufactured Equipment, Expressed as a Percentage of Emissions from New Equipment[a]

	United States				Europe[b]				Japan, Australia, & New Zealand				All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean, Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																								
Refrigerant recovery from small equipment	ND				ND				ND				ND				ND				ND			
Leak repair for large equipment	ND				ND				ND				ND				ND				ND			
Technology Options																								
Ammonia secondary loop	3	5	13	20	5	10	13	15	5	10	13	15	5	10	13	15	5	10	10	10	5	10	10	10
Distributed system	8	15	23	30	10	20	30	40	10	20	30	40	10	20	30	40	8	15	20	25	8	15	20	25
HFC secondary loop system	8	15	23	30	5	10	18	25	5	10	18	25	5	10	18	25	8	10	13	20	8	10	13	20
Enhanced HFC-134a in MVACs	0	40	50	60	0	0	0	0	0	40	50	60	0	40	50	60	0	5	20	40	0	5	20	40
HFC-152a in MVACs	0	1	20	30	0	1	15	25	0	1	20	30	0	1	20	30	0	0	1	20	0	0	1	20
CO_2 in MVACs	0	1	5	10	0	15	65	75	0	1	5	10	0	1	5	10	0	0	1	5	0	0	1	5

[a] Expressed as a percentage of new equipment for the given year. The baseline market penetration of all technology options is assumed to be zero so that only incremental market penetration is analyzed.

[b] Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia.

ND: No distinction was made between market penetration assumptions into new versus existing equipment.

Table 2-19: Market Penetration of Abatement Options, Expressed as a Percentage of Total Sector Emissions[a]

	United States				Europe[c]				Japan, Australia, & New Zealand				All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean, Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																								
Refrigerant recovery from small equipment[b]	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	5.0	10.0	10.0	15.0	20.0	30.0	40.0	50.0	20.0	30.0	40.0	50.0
Leak repair for large equipment	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	3.0	3.0	5.0	5.0	5.0	10.0	12.0	15.0	5.0	10.0	12.0	15.0
Technology Options																								
Ammonia secondary loop	0.2	1.4	4.3	9.4	0.3	2.6	6.1	10.3	0.3	2.6	6.1	10.3	0.3	2.6	6.1	10.3	0.3	2.6	5.6	8.5	0.3	2.6	5.6	8.5
Distributed system	0.5	4.1	9.9	17.9	0.6	5.3	12.9	23.5	0.6	5.3	12.9	23.5	0.6	5.3	12.9	23.5	0.5	4.1	9.4	16.1	0.5	4.1	9.4	16.1
HFC secondary loop system	0.5	4.1	9.9	17.9	0.3	2.6	7.0	13.5	0.3	2.6	7.0	13.5	0.3	2.6	7.0	13.5	0.5	3.2	6.6	11.7	0.5	3.2	6.6	11.7
Enhanced HFC-134a in MVACs	0.0	10.0	29.2	48.5	0.0	0.0	0.0	0.0	0.0	10.0	29.2	48.5	0.0	10.0	29.2	48.5	0.0	1.3	7.1	19.9	0.0	1.3	7.1	19.9
HFC-152a in MVACs	0.0	0.3	5.4	16.2	0.0	0.3	4.2	12.8	0.0	0.3	5.4	16.2	0.0	0.3	5.4	16.2	0.0	0.0	0.3	5.4	0.0	0.0	0.3	5.4
CO_2 in MVACs	0.0	0.3	1.7	4.9	0.0	3.8	22.5	50.6	0.0	0.3	1.7	4.9	0.0	0.3	1.7	4.9	0.0	0.0	0.3	1.7	0.0	0.0	0.3	1.7

[a] Total sector emissions include those from new and existing equipment (i.e., the entire installed base). The baseline market penetration is assumed to be zero, unless otherwise noted.
[b] Shown percentage values are incremental relative to the baseline market penetration, which is assumed to be 80 percent in developed countries and 30 percent in developing countries.
[c] Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia.

Table 2-20: Percentage of (Direct)[a] Reduction Off Baseline Emissions of All Abatement Options by Region

	United States				Europe[b]				Japan				Australia and New Zealand			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																
Refrigerant recovery from small equipment	1.1	2.1	2.1	3.3	1.3	2.5	2.4	3.9	1.1	2.1	2.1	3.3	1.3	2.5	2.4	3.9
Leak repair for large equipment	0.3	0.3	0.5	0.5	0.2	0.2	0.4	0.4	0.3	0.3	0.5	0.5	0.2	0.2	0.4	0.4
Technology Options																
Ammonia secondary loop	0.1	0.6	1.8	3.8	0.1	0.9	2.3	3.3	0.1	1.1	2.6	4.2	0.1	0.9	2.3	3.3
Distributed system	0.2	1.6	3.8	6.5	0.2	1.6	4.4	6.8	0.2	2.1	5.0	8.6	0.2	1.6	4.4	6.8
HFC secondary loop system	0.2	1.6	3.9	6.8	0.1	0.8	2.5	4.1	0.1	1.1	2.8	5.1	0.1	0.8	2.5	4.1
Enhanced HFC-134a in MVACs	0.0	1.4	3.3	4.8	0.0	0.0	0.0	0.0	0.0	1.4	3.3	4.8	0.0	2.1	4.6	8.9
HFC-152a in MVACs	0.0	0.1	1.1	2.9	0.0	0.1	1.2	4.2	0.0	0.1	1.1	2.9	0.0	0.1	1.5	5.3
CO_2 in MVACs	0.0	0.1	0.4	1.0	0.0	1.6	7.2	18.5	0.0	0.1	0.4	1.0	0.0	0.1	0.5	1.8

	All Other Annex I Countries				China, Hong Kong, & India				Latin America & Caribbean				Russian Federation, Ukraine, & All Other Non-Annex I Countries			
	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020	2005	2010	2015	2020
Practice Options																
Refrigerant recovery from small equipment	1.3	2.5	2.4	3.9	4.8	8.5	12.8	16.8	3.0	4.9	7.3	9.9	2.4	4.0	6.5	9.4
Leak repair for large equipment	0.2	0.2	0.4	0.4	0.4	0.7	0.6	0.6	0.6	1.2	1.4	1.6	0.7	1.4	1.5	1.7
Technology Options																
Ammonia secondary loop	0.1	0.9	2.3	3.3	0.1	0.7	1.2	1.5	0.2	1.4	2.7	3.8	0.2	1.5	2.9	4.0
Distributed system	0.2	1.6	4.4	6.8	0.2	1.0	1.8	2.5	0.2	1.9	4.0	6.5	0.3	2.1	4.4	6.8
HFC secondary loop system	0.1	0.8	2.5	4.1	0.2	0.8	1.3	1.9	0.2	1.5	3.0	4.9	0.3	1.7	3.2	5.1
Enhanced HFC-134a in MVACs	0.0	2.1	4.6	8.9	0.0	0.3	2.2	6.6	0.0	0.1	0.4	1.2	0.0	0.0	0.2	0.8
HFC-152a in MVACs	0.0	0.1	1.5	5.3	0.0	0.0	0.1	3.2	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.4
CO_2 in MVACs	0.0	0.1	0.5	1.8	0.0	0.0	0.2	1.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1

[a] Direct reductions refer to HFC emissions reductions; indirect emissions impacts associated with energy consumption are not reflected in this table (and are not included in the baseline).

[b] Europe is assumed to include the EU-25 countries, Croatia, Norway, Romania, Switzerland, Turkey, Bulgaria, and Macedonia.

Table 2-21: Summary of Abatement Option Cost Assumptions (2000$)

Option	Time Horizon (Years)	Unit of Costs	U.S. One-Time Cost	U.S. Annual Cost	U.S. Annual Savings	Net U.S. Annual Costs
Refrigerant recovery	1	Per recovery job	—[a]	$10.10	$13.71	–$3.61
Distributed system	15	Per 60,000 ft^2 supermarket	$7,200.00	$2,796.19[b]	$3,559.94	–$763.75
Secondary loop	15	Per 60,000 ft^2 supermarket	$25,200.00	$5,592.38[b]	$3,691.79	$1,900.59
Ammonia secondary loop	15	Per 60,000 ft^2 supermarket	$36,000.00	$5,592.38[b]	$3,955.49	$1,636.89
Leak repair	1	Per repair job	$1,480.00[c]	—	$2,636.99	–$2,636.99
CO_2 for new MVACs	12	Per MVAC	$105.30	—	$18.35[d]	–$18.35
Enhanced HFC-134a in MVACs	12	Per MVAC	$42.12	—	$21.38[d]	–$21.38
HFC-152a in MVACs	12	Per MVAC	$23.69	—	$7.92[e]	–$7.92

[a] The cost of a high-pressure recovery unit is assumed to be approximately $860, but all costs associated with this option, including capital costs, are annualized and expressed in terms of cost per job.

[b] In all other countries, this annual cost was adjusted by average electricity prices (average of 1994–1999) based on USEIA (2000).

[c] Includes parts and labor to perform repair job.

[d] Annual U.S. costs savings are associated with gasoline and refrigerant savings. For all other countries, the annual saving associated with gasoline in the United States is adjusted by the estimated amount of gasoline saved per vehicle per year (based on Rugh and Hovland [2003]) and by average regional costs of unleaded gasoline in 2003 (based on USEIA [2005]). No adjustments are made to the savings associated with refrigerant.

[e] Annual U.S. costs savings are associated with gasoline savings. For all other countries, this annual savings is adjusted by the estimated amount of gasoline saved per vehicle per year (based on Rugh and Hovland [2003]) and by average regional costs of unleaded gasoline in 2003 (based on USEIA [2005]).

Table 2-22: Country/Regional Emissions Reductions in 2010 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate ($/tCO$_2$eq)

Country/Region	2010					
	$0	$15	$30	$45	$60	>$60
Africa	0.69	1.04	1.37	1.37	1.37	1.37
Annex I	**9.08**	**17.51**	**18.63**	**18.63**	**19.34**	**19.38**
Australia/New Zealand	0.09	0.20	0.27	0.27	0.27	0.27
Brazil	0.42	0.75	0.76	0.76	0.76	0.76
China & Hong Kong	2.63	3.03	3.12	3.12	3.12	3.12
Eastern Europe	0.15	0.27	0.27	0.27	0.34	0.34
EU-15	1.08	2.25	2.36	2.36	2.97	2.97
India	0.24	0.29	0.31	0.31	0.31	0.31
Japan	1.22	1.91	2.63	2.63	2.63	2.65
Mexico	0.40	0.72	0.73	0.73	0.73	0.73
Non-OECD Annex I	**0.62**	**0.90**	**0.91**	**0.91**	**0.94**	**0.94**
OECD	**9.86**	**19.32**	**20.44**	**20.44**	**21.12**	**21.16**
Russian Federation	0.52	0.74	0.75	0.75	0.75	0.75
South & SE Asia	0.79	1.57	1.57	1.57	1.57	1.57
United States	5.67	11.44	11.44	11.44	11.44	11.44
World Total	**16.60**	**29.20**	**31.03**	**31.03**	**31.73**	**31.77**

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

Table 2-23: Country/Regional Emissions Reductions in 2020 and Breakeven Costs for Refrigeration/Air-Conditioning at 10% Discount Rate, 40% Tax Rate ($/tCO$_2$eq)

Country/Region	2020					
	$0	$15	$30	$45	$60	>$60
Africa	2.26	4.06	5.73	5.73	5.73	5.76
Annex I	**43.63**	**109.62**	**117.89**	**117.89**	**130.65**	**131.50**
Australia/New Zealand	0.24	1.03	1.81	1.81	1.81	1.91
Brazil	1.38	3.19	3.41	3.41	3.41	3.43
China & Hong Kong	12.33	14.41	20.41	20.41	20.41	21.09
Eastern Europe	0.81	1.66	1.66	1.66	2.96	2.96
EU-15	4.95	12.48	13.22	13.22	24.03	24.03
India	0.94	1.18	1.79	1.79	1.79	1.85
Japan	3.87	9.03	13.22	13.22	13.22	13.66
Mexico	1.29	2.99	3.19	3.19	3.19	3.22
Non-OECD Annex I	**2.89**	**4.49**	**4.74**	**4.74**	**5.25**	**5.28**
OECD	**45.69**	**117.04**	**125.65**	**125.65**	**137.90**	**138.79**
Russian Federation	2.39	3.60	3.76	3.76	3.76	3.78
South & SE Asia	3.11	7.56	7.89	7.89	7.89	7.93
United States	30.26	78.05	78.05	78.05	78.05	78.05
World Total	**73.22**	**161.70**	**181.11**	**181.11**	**193.94**	**195.80**

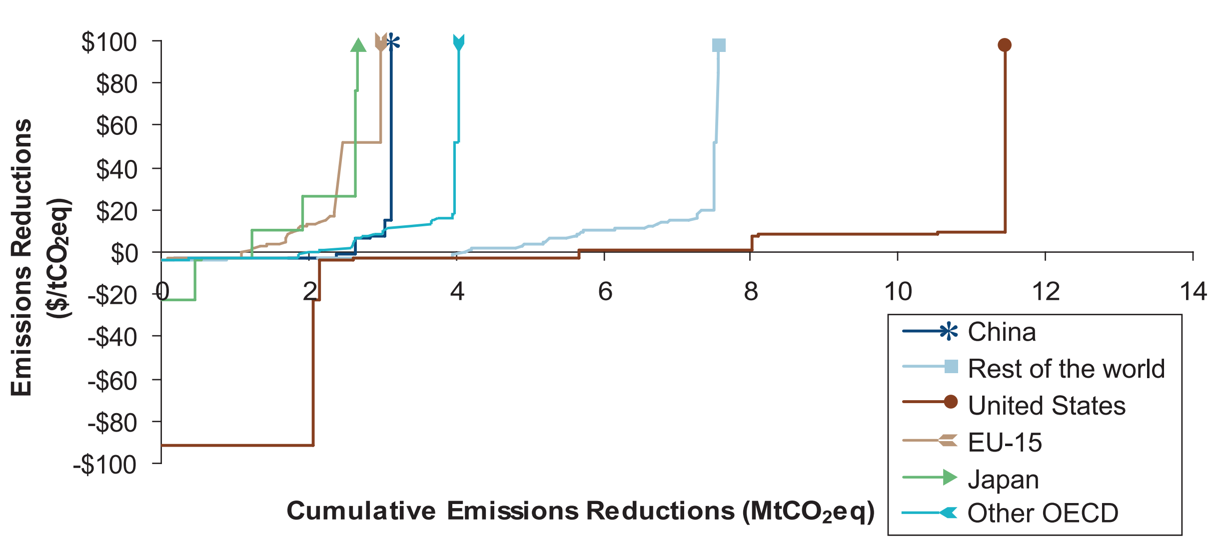
EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 2-24: World Breakeven Costs and Emissions Reductions in 2020 for Refrigeration/Air-Conditioning

Reduction Option	Cost (2000$/t$CO_2$eq) DR=10%, TR=40% Low	High	Direct Emissions Reduction[a] (MtCO_2eq)	Indirect Emissions Reduction[b] (MtCO_2eq)	Reduction from 2020 Baseline (%)	Running Sum of Reductions (MtCO_2eq)	Cumulative Reduction from 2020 Baseline (%)
Leak repair	–$4.10	–$4.10	4.91	0.00	0.8%	4.91	0.8%
Refrigerant recovery	–$2.62	–$2.62	40.16	0.00	6.4%	45.07	7.2%
Distributed system	–$1.08	$9.99	39.67	–0.43	6.3%	84.74	13.5%
Enhanced HFC-134a in MVACs	–$175.92	$16.21	22.69	21.67	3.6%	107.44	17.1%
HFC-152a in MVACs	–$27.59	$18.18	15.72	0.81	2.5%	123.16	19.6%
Ammonia secondary loop	$6.33	$26.40	22.18	–2.71	3.5%	145.34	23.2%
HFC secondary loop	$4.81	$26.70	33.20	–0.06	5.3%	178.54	28.5%
CO_2 for new MVACs	$7.57	$91.60	17.26	1.83	2.8%	195.80	31.2%

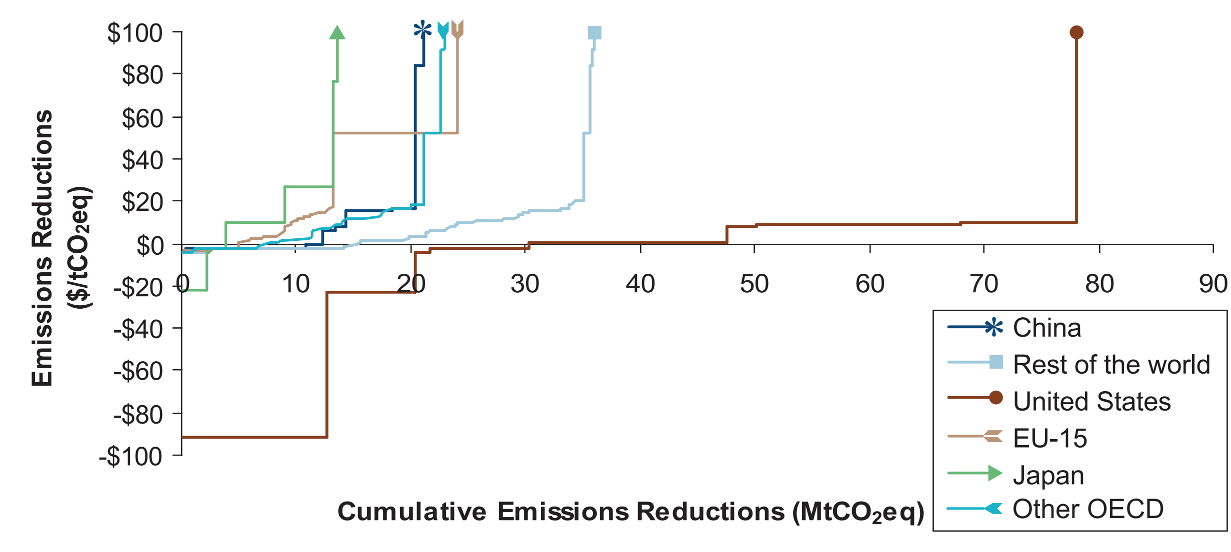
[a] Direct reductions refer to HFC emissions reductions (off the baseline).
[b] Indirect emissions impacts are those associated with energy consumption (not included in the baseline).

Figure 2-2: 2010 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate



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

Figure 2-3: 2020 MAC for Refrigeration/Air-Conditioning, 10% Discount Rate, 40% Tax Rate



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

IV.2.4.2 Uncertainties and Limitations

This section focuses on the uncertainties and limitations of the cost estimates presented in this analysis. One significant area of uncertainty is how capital costs for these mitigation technologies may vary internationally. The analysis is currently limited by the lack of this specificity on region-specific cost analysis estimates. In addition, the main uncertainties related to the following abatement options are listed below.

Leak Repair for Large Equipment

Because leak repair can be performed on many different equipment types and can involve many different activities/tools, it is difficult to determine an average cost of such repairs or the average emissions reduction associated with them. This analysis, therefore, relies on broad assumptions available in the published literature, which may not reflect specific or even average values for the leak repair activities modeled.

Refrigerant Recovery for Small Equipment

Estimates of the amount of refrigerant recoverable from MVACs and small appliances at service and disposal are highly uncertain. This analysis uses the estimates provided in USEPA (1998).

Stationary Technology Options (Distributed, HFC Secondary Loop, and Ammonia Secondary Loop Systems)

This analysis assumes that emissions savings equal to 56 percent of the original equipment charge are realized at disposal in the distributed and HFC and ammonia secondary loop options; however, the actual amount of charge emitted at disposal is uncertain.

IV.2.5 Summary

Baseline HFC emissions from refrigeration and air-conditioning are expected to grow significantly between 2005 and 2020, as HFCs become used increasingly throughout the world to replace gases phased out under the Montreal Protocol. The highest percentage of emissions growth is expected to occur in developing countries.

This analysis considers the costs and emissions reduction potential of eight practice and technology emissions mitigation options: (1) leak repair for large equipment, (2) refrigerant recovery and recycling from small equipment, (3) distributed system, (4) HFC secondary loop, (5) ammonia secondary loop, (6) enhanced HFC-134a systems in MVACs, (7) HFC-152a systems in MVACs, and (8) CO_2 systems in MVACs. The costs and emissions reduction benefits of each option were compared for each region. Increasing leak repair of large equipment and refrigerant recovery/recycling from small equipment represent cost-effective options for reducing emissions from stationary equipment worldwide. For MVACs, the enhanced HFC-134a option represents the most cost-effective alternative for reducing emissions.

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