# IV. Industrial Processes Sector

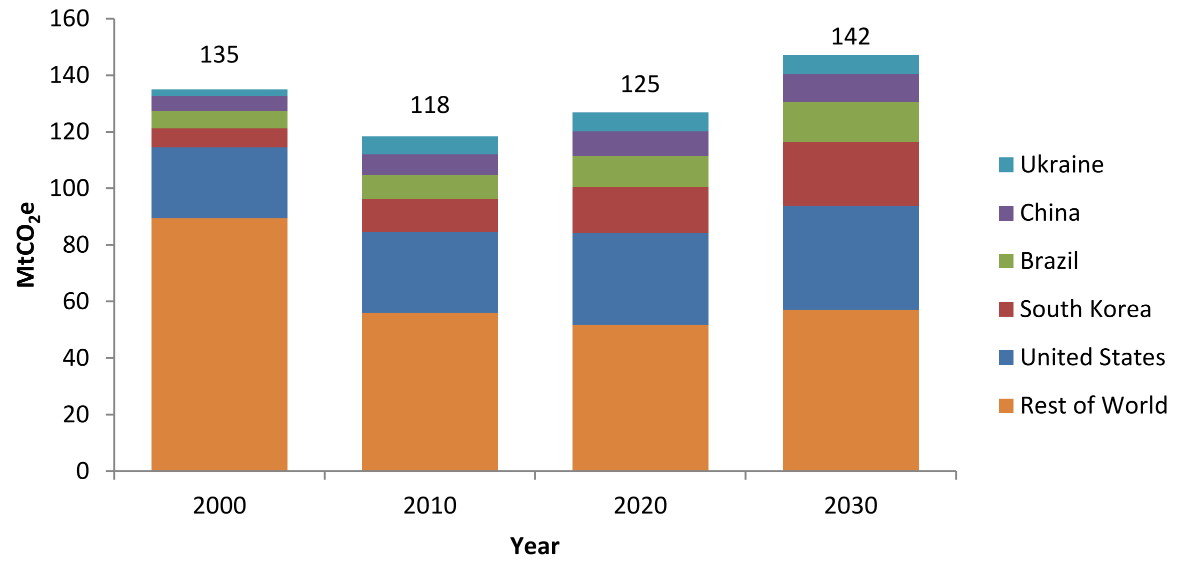
# IV.1. Nitric and Adipic Acid Production

## IV.1.1 Sector Summary

The production of nitric and adipic acid results in significant nitrous oxide ($N_2O$) emissions as a by-product. Nitric and adipic acid are commonly used as feedstocks in the manufacture of a variety of commercial products, particularly fertilizers and synthetic fibers (USEPA, 2012a).

Combined global emissions of $N_2O$ from nitric and adipic acid production are shown in Figure 1-1. Globally, emissions have declined by about 13% (17 $MtCO_2e$) over the past decade; however, over the next 20 years—2010 to 2030—emissions are expected to increase steadily (~20%) growing by 24 $MtCO_2e$ over the time period. This trend is largely due to increased demand for fertilizer (nitric acid is an input) and increased demand for synthetic fibers (adipic acid is an input). In 2030, the United States, South Korea, Brazil, China, and Ukraine are expected to be five largest emitters of $N_2O$ from nitric and adipic acid production.

**Figure 1-1: $N_2O$ Emissions from Nitric and Adipic Acid: 2000–2030**

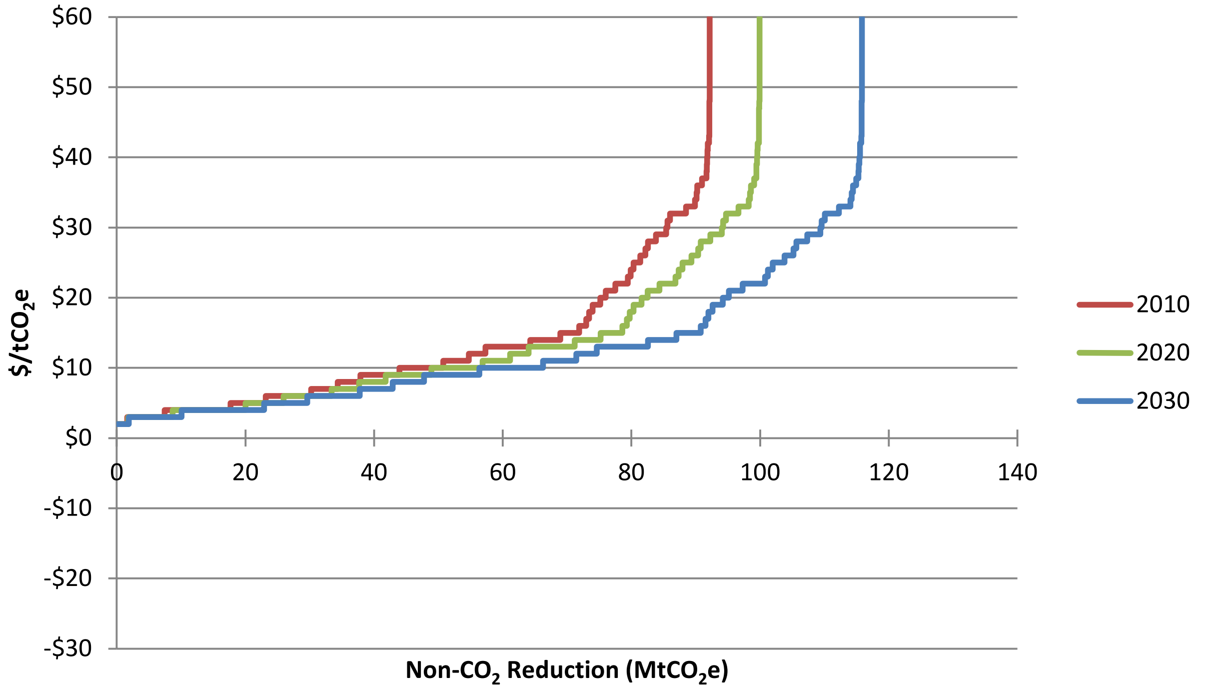


Source: USEPA, 2012a.

Over the coming decades, increased demand for adipic acid in Asia is expected to contribute to higher $N_2O$ emissions from adipic acid production, while abatement control technologies employed at adipic acid production facilities in the 1990s in the United States, Canada, and some countries of the EU are expected to reduce $N_2O$ emissions (USEPA, 2012a). Overall, increased global demand for adipic acid is expected to have the effect of higher annual $N_2O$ emissions resulting from adipic acid production. In addition, global $N_2O$ emissions from nitric acid are expected to increase as demand for nitrogen-based fertilizer increases. Although concerns about nutrient run-off have caused some countries to reduce their demand for nitrogen-based fertilizer, growing world demand for agricultural commodities is expected to have the effect of increasing nitric acid production and, consequently, $N_2O$ emissions.

Global abatement potential of $N_2O$ in nitric acid and adipic acid production is 98 and 115 $MtCO_2e$ in 2020 and 2030, respectively. These results are depicted in the sectoral marginal abatement cost (MAC) curves in Figure 1-2. As the MAC curves show, roughly 45% of the maximum abatement potential in each year is achievable at relatively low carbon prices (between \$2 and \$10 $tCO_2e^{-1}$).

**Figure 1-2: Global MAC for Nitric and Adipic Acid: 2010, 2020, and 2030**



The following section provides a brief explanation of the manufacturing processes that result in the formation of $N_2O$ emissions. Next we discuss the projected emissions from these processes out to 2030. Subsequent sections characterize the abatement measures and present the cost of implementation and operation for each. The chapter concludes with a discussion of the MAC analysis approach unique to this sector and the regional results.

## IV.1.2 $N_2O$ Emissions from Nitric and Adipic Acid Production

$N_2O$ emissions are closely correlated with the production of nitric and adipic acid. The following section discusses global production activity data, typical emissions factors, and baseline emissions estimates of $N_2O$ from nitric and adipic acid production. The MAC analysis presented here starts by assuming the projected emissions presented in USEPA's 2012 Global Emissions Report (2012a). This analysis then derives industry activity from the USEPA emissions projections based on current industrial activity.

### IV.1.2.1 Nitric Acid Production and Emission Factors

Ammonium nitrate production represents the largest demand market for nitric acid, with the majority of nitric acid being consumed by ammonium nitrate producers. The demand for ammonium nitrate products, especially fertilizer, is the main driver of nitric acid demand. Nitric acid production levels closely follow trends in fertilizer demand (Mainhardt and Kruger, 2000). Trends in fertilizer demand vary widely across different regions of the world. For example, in Western Europe, because of concerns over nutrient runoff and nitrates in the water supply, use of nitrogen-based fertilizer has been significantly reduced in the past couple of decades (USEPA, 2012a). Despite this trend, the European Fertilizer Manufacturers Association (EFMA) is predicting modest growth in demand of 1.3% annually over this decade. In other parts of the world, a continued desire to secure domestic fertilizer production capacity to supplant reliance on imports in combination with expansions in capacity for large fertilizer consuming countries are expected to result in a net increase in nitrogen-based fertilizer production capacity between 2010 and 2015 (IFA, 2011). Globally, over the next several decades, increases in food consumption and demand for agricultural products will continue to put upward pressure on fertilizer demand, which, in turn, is expected to increase the demand and consumption of nitric acid.

The actual number of nitric acid production plants globally is unknown. Previous reports cited by the Intergovernmental Panel on Climate Change (IPCC) have suggested the number to be between 255 and 600. More recent estimates suggest that between 500 and 600 plants were in operation in 2010 (Kollmus and Lazarus, 2010). The actual number is uncertain because many nitric acid plants are often part of larger integrated chemical facilities that manufacture products using nitric acid—in the production of a wide range of chemical products such as fertilizer and explosives (Kollmus and Lazarus, 2010; Mainhardt and Kruger, 2000).

As noted earlier, global nitric acid production is expected to increase over time. Projections in nitric acid production levels by country are not publicly available.

The IPCC reports that $N_2O$ emissions factors for nitric acid production also 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 operating pressure of the plant, the type of nitrogen oxide ($NO_x$) control technology (if any) deployed on the plant, and whether $N_2O$ abatement has been implemented. As shown in Table 1-1, $N_2O$ emission rates increase as the plant operating pressure increases. Furthermore, non-selective catalytic reduction (NSCR) is very effective at destroying $N_2O$, whereas other technologies used to control $NO_x$ emissions, such as selective catalytic reduction (SCR) and extended absorption, do not reduce $N_2O$ emissions.

**Table 1-1: IPCC Emissions Factors for Nitric Acid Production**

| Production Process | $N_2O$ Emissions Factor (relating to 100% pure acid) |
|---|---|
| **Plants with NSCR[a] (all processes)** | 2 kg $N_2O$/tonne nitric acid ±10% |
| **Plants with process-integrated or tailgas $N_2O$ destruction** | 2.5 kg $N_2O$/tonne nitric acid ±10% |
| **Atmospheric pressure plants (low pressure)** | 5 kg $N_2O$/tonne nitric acid ±10% |
| **Medium pressure combustion plants** | 7 kg $N_2O$/tonne nitric acid ±20% |
| **High pressure plants** | 9 kg $N_2O$/tonne nitric acid ±40% |

Source: IPCC, 2006.

[a] Non-selective catalytic reduction (NSCR)

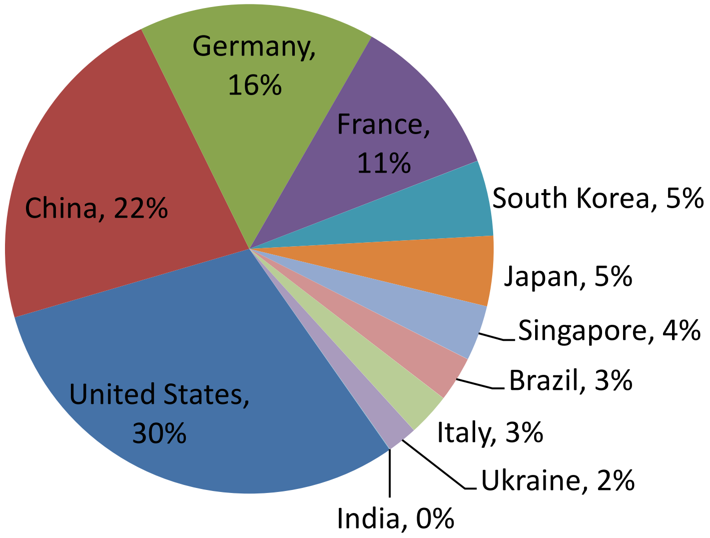
The IPCC notes that emissions factors as high as 19.5 kilograms $N_2O$ per ton of nitric acid produced have been previously estimated. In addition, some estimates indicate that 80% of the nitric acid plants worldwide do not employ NSCR technology, which makes it more likely that the default range of potential emissions factors provided by the IPCC underestimates the true emissions baselines (Mainhardt and Kruger, 2000). Therefore, the uncertainties associated with these emission factors may be higher than listed in Table 1-1. However, no uncertainty assessments other than the IPCC's have been published, so without more information, this analysis relies on the published values above.

### IV.1.2.2 Adipic Acid Production and Emission Factors

Adipic acid is used primarily in the production of synthetic fibers, predominantly as a precursor for the production on nylon 6,6 (The Chemical Company [CC], 2010a). As a result, production of adipic acid is closely correlated with the world's nylon production. Worldwide, the largest single use of adipic acid is in carpet manufacturing, accounting for 30% of the market (USEPA, 2012a; *Chemical Week*, 2007).

Global demand for adipic acid is expected to increase over the next few decades, particularly in Asia, driven primarily by the growth in demand for synthetic fibers (i.e., nylon 6,6), particularly for use in carpet manufacturing. Nylon 6,6 accounts for approximately 90% of adipic acid demand; demand for nylon is a strong indicator of future adipic acid demand (CC, 2010b). Future production of adipic acid is expected to closely following the demand trend for synthetic fibers. Figure 1-3 shows the share of adipic acid production capacity by country in 2010.

**Figure 1-3: Adipic Acid Production Capacity by Country: 2010**



Global capacity in 2010 was approximately 3 million metric tons, concentrated in the United States (30%), the European Union (29%), and China (22%) (Schneider, Lazarus, and Kollmuss, 2010; USEPA, 2012b). In the same year, global production of adipic acid was approximately 2.5 million metric tons (CC, 2010a). Plants in located in Canada and the United Kingdom were recently shut down and two of four facilities in the United States were idle in 2009 and assumed to remain so in 2010 (USEPA, 2012b).

The IPCC provides a default emissions factor of 300 kilograms ± 10% $N_2O$ per ton of adipic acid produced (IPCC, 2006). This emissions factor assumes that no $N_2O$ control system is in place. Additionally, this factor should be used only when national total data are available and plant-level data are deemed unreliable. 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. The IPCC recommends using plant-specific data for those plants with abatement controls already in place and reliable plant-level data (IPCC, 2006).

### IV.1.2.3 Emissions Estimates and Related Assumptions

This section discusses the historical and projected baseline emissions from the production of nitric and adipic acid.[1] Historical emissions are characterized as those emissions released from the 1990 to 2010 period and projected emissions estimates cover the period from 2010 to 2030.

#### *Historical Emissions Estimates*

Between 1990 and 2005, $N_2O$ emissions from nitric and adipic acid production decreased by 37% down from 200 $MtCO_2e$ in 1990 to 126 $MtCO_2e$ in 2005. Key factors that influence emissions are the demand for final products that include intermediates of nitric and adipic acid such as carpet and fertilizers. Although demand for and production of nitric and adipic acid increased over the 1990 to 2005 time period, $N_2O$ emissions actually decreased over the period. The reductions in $N_2O$ emissions over this period were mostly due to the installation of abatement technologies in the adipic acid industry (USEPA, 2012a).

#### *Projected Emissions Estimates*

Table 1-2 lists the combined projected $N_2O$ baseline emissions from nitric and adipic acid production by country/region and year. Worldwide $N_2O$ emissions are projected to increase by approximately 21% (24 $MtCO_2e$) between 2010 and 2030. South Korea, Canada, and Brazil are expected to experience the largest percentage increase in baseline emissions over the 2010 to 2030 period, with increases of 93, 77, and 68%, respectively. The United States is expected to have the second largest absolute increase (8 $MtCO_2e$) in emissions, which represents a 28% increase from 2010, while South Korea is expected to have the largest absolute increase (11 $MtCO_2e$).

## IV.1.3 Abatement Measures and Engineering Cost Analysis

This analysis considered four abatement measures applied to the chemical processes used to produce nitric and adipic acid to reduce the quantity of nitrous oxide ($N_2O$) emissions released during the production process. Thermal destruction is the abatement measure applied to the adipic acid production process. The three remaining measures were applied to the nitric acid production process.

Nitric acid facilities have the option of using specially designed catalysts to control $N_2O$ emissions. The location of catalyst placement within the nitric acid production process determines the catalyst design, composition, and terminology. Abatement measures applicable to nitric acid are characterized by where in the production process they are implemented. These options include primary abatement, secondary abatement, and tertiary abatement. Primary abatement measures occur within the ammonia burner, preventing the formation of $N_2O$. Secondary abatement measures such as homogeneous thermal decomposition and catalytic decomposition are installed at an intermediate point in the production process, removing the $N_2O$ formed through ammonia oxidation. Tertiary abatement measures, such as catalytic decomposition and NSCR units are applied to the tail gas streams at the end of the nitric acid

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[1] For more detail on baseline development and estimation methodology, we refer the reader to the USEPA's *Global Emissions Projection Report.* Available at: http://www.epa.gov\climatechange\economics\international.html.

**Table 1-2: Projected $N_2O$ Baseline Emissions from Nitric and Adipic Acid Production: 2010–2030**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| United States | 29 | 30 | 32 | 35 | 37 | 1.2% |
| South Korea | 12 | 14 | 16 | 19 | 23 | 3.4% |
| Brazil | 8 | 9 | 11 | 12 | 14 | 2.6% |
| China | 7 | 8 | 9 | 10 | 10 | 1.6% |
| Ukraine | 6 | 7 | 7 | 7 | 7 | 0.4% |
| **Rest of Region** | | | | | | |
| Africa | 3 | 3 | 3 | 4 | 3 | 0.1% |
| Central & South America | 1 | 2 | 2 | 2 | 2 | 0.4% |
| Middle East | 1 | 1 | 1 | 1 | 1 | 0.5% |
| Europe | 32 | 25 | 25 | 25 | 29 | −0.5% |
| Eurasia | 7 | 7 | 7 | 7 | 7 | 0.2% |
| Asia | 9 | 10 | 10 | 11 | 12 | 1.3% |
| North America | 2 | 3 | 3 | 3 | 4 | 2.3% |
| **World Total** | **118** | **118** | **127** | **136** | **147** | **1.1%** |

[a] CAGR = Compound Annual Growth Rate

[b] Mexico is the only country included under North America, as Canada and the United States are reported individually above.

Source: USEPA, 2012a.

production process. The implementation of one technology over another is driven largely by facility design constraints and/or cost considerations. The high operating costs of NSCR units and improvement in modern facility design will drive most future abatement projects to adopt secondary or tertiary catalysts over NSCR units.

This section briefly characterizes each abatement measure and the supporting technical assumptions that were used to compute the breakeven prices. Table 1-3 summarized the costs and technical assumptions for the four abatement measures. Abatement measure costs were derived from a variety of sources reporting in euros and dollars over a number of base years. For consistency, we assumed a fixed exchange rate of 1.32 (USD/EUR), and the Chemical Engineering Plant Cost Index (CEPI) was used to adjust costs for inflation. Consistent with other sectors evaluated in this study, the costs of abatement developed for this analysis exclude capital and O&M costs attributable to monitoring, reporting, and verification (MRV) activities.

### IV.1.3.1 Adipic Acid—$N_2O$ Abatement Methods

Adipic acid facilities typically direct the flue gas to a reductive furnace in a thermal destruction process to reduce nitric oxide ($NO_X$) emissions. Thermal destruction is the combustion of off-gases (including $N_2O$) in the presence of methane. The combustion process converts $N_2O$ to nitrogen, resulting primarily in emissions of NO and some residual $N_2O$ (Ecofys, Fraunhofer ISIR, and Öko-Institute, 2009). Facilities may also employee a catalytic decomposition method to abatement $N_2O$ generated. The EU Emissions Trading System [ETS] and CDM methodologies for this abatement measure suggest that heat generated from the decomposition of $N_2O$ can be used to produce process steam for utilization in local processes, substituting for more expensive steam generated using fossil fuel alone. For this analysis, we assume the abatement measures' conversion of $N_2O$ to nitrogen technical effectiveness is 95%. Costs presented below are based on a catalytic decomposition method.

Table 1-3: Abatement Measures for Nitric and Adipic Acid Production

| | 2010 USD | | | | Annual Benefits | | |
|---|---|---|---|---|---|---|---|
| Abatement Option | Total Installed Capital Cost | Annual O&M Cost | Time Horizon (Years) | Technical Efficiency,% | Energy | Non-energy | Average Reductions ($tCO_2e/yr$) |
| **Adipic Acid Production[a]** | | | | | | | |
| Thermal/catalytic decomposition | 11.4 | 2.2 | 20 | 96% | — | 0.3 | **4,206,218** |
| **Nitric Acid Production[b]** | | | | | | | |
| **Secondary Abatement—**<br>Catalytic decomposition in the burner | 1.3 | 0.4 | 15 | 85% | — | — | **779,571** |
| **Tertiary Abatement—**<br>Direct catalytic decomposition | 2.3 | 0.2 | 15 | 95% | — | — | **871,286** |
| **Tertiary Abatement—**<br>Non-selective catalytic reduction unit | 4.0 | 2.1 | 20 | 95% | — | — | **871,286** |

[a] Based on adipic acid plant capacity of 200 metric tons of adipic acid per day.

[b] Based on nitric acid plant capacity of 1,000 $tHNO_3$/day.

- **Capital Costs:** Initial capital costs are $156 per metric ton of production capacity in 2010 dollars. This cost includes the costs of engineering design and process modifications in addition to equipment and installation costs. Assuming a plant with capacity of 200 tonnes adipic acid production per day, the initial capital cost would be approximately $11.4 million (2010 USD).
- **Annual O&M Costs:** Annual costs total $38 per metric ton of production in 2010 dollars, which includes the costs of annual energy requirements and system maintenance. Assuming a plant with capacity of 200 tonnes and a utilization factor of 80%, the annual operating cost would be $2.2 million (2010 USD). Catalyst consumption represents 60% of the annual costs.
- **Annual Benefits:** Steam produced through the decomposition of $N_2O$ under this abatement measure can offset steam generated using more expensive energy sources providing a fuel cost savings. These annual benefits can equal up to 60% of operating costs (Ecofys et al., 2009). This analysis assumes a more conservative estimate of 16% of operating costs or $5.6 per metric ton of adipic acid production based on CDM project documentation.
- **Applicability:** This option applies to adipic acid production facilities that do not currently control $N_2O$ emissions. Based on recent analysis (Schneider et al., 2010), only 9 of the 23 operational facilities in 2010 had unabated $N_2O$ emissions.
- **Technical Effectiveness:** This analysis assumes a 95% efficiency converting $N_2O$ into nitrogen and water.
- **Technical Lifetime:** 20 years

### IV.1.3.2 Nitric Acid—Primary Abatement Measures

This group of abatement measures can be applied at the ammonia oxidation stage of the nitric acid production process. Perez-Ramirez (2003) identified three alternative approaches categorized as primary abatement options: optimized oxidation, modification of the Pt-Rh gauzes, and oxide-based combustion catalysts. All three technologies prevent the formation of $N_2O$ in the ammonia burner and would require making adjustments to the ammonia oxidation process and/or catalyst (Perez-Ramirez, 2003). Although the primary abatement technology options are technically feasible, they are not modeled in this analysis because of a lack of technology cost data and the fact that the alternative options discussed below achieve greater abatement and are better defined.

### IV.1.3.3 Nitric Acid—Secondary Abatement Measures

Secondary abatement measures remove $N_2O$ immediately following the ammonia oxidation stage, between the ammonia converter and the absorption column (Perez-Ramirez, 2003). Abatement measures include thermal decomposition, catalytic decomposition inside or immediately following the ammonia burner. Thermal decomposition, developed by Norsk Hydro in the 1990s, is better suited for inclusion in new plants, because it requires redesigning the reaction chamber immediately following the ammonia burner. This design change can increase the capital cost of a new plant by 5 to 6% but has no impact on operating costs (Perez-Ramirez, 2003). The catalytic decomposition option is better suited for retrofitting and can be incorporated as an add-on technology at minimal cost. For this analysis, the catalytic decomposition costs were used as the representative costs of the secondary abatement option.

- **Capital Costs:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumes a capital cost of \$3.5/tonne of $HNO_3$ production capacity[2] and a plant capacity of 1,000 $tHNO_3$/day. Using these assumptions, the initial capital costs would equal \$1.3 million (2010 USD).
- **Annual O&M Costs:** Annual costs include catalyst replacement and recycling of spent catalyst, replacement of spare catalyst, and loss of production due to catalyst disruptions. This analysis assumes an annual cost of \$1.3/$tHNO_3$ produced and a plant utilization rate of 90% (Perez-Ramirez, 2003). Following the plant example of a 1,000 $tHNO_3$/day, the annual cost would be \$0.4 million (2010 USD).
- **Annual Benefits:** No benefits are associated with this option.
- **Applicability:** This option is applicable to all existing nitric acid plants.
- **Technical Effectiveness:** This analysis assumes an 80% efficiency converting $N_2O$ into nitrogen and water.
- **Technical Lifetime:** 20 years

### IV.1.3.4 Nitric Acid—Tertiary Abatement Measure: Direct Catalytic Decomposition

Tertiary abatement measures are located after the absorption tower where tail gas leaving the absorption column is treated to destroy $N_2O$ (Perez-Ramirez, 2003). Similar to earlier abatement measures, this measure reduces the $N_2O$ into nitrogen and oxygen, through thermal or catalytic decomposition.

- **Capital Costs:** Capital costs include the purchase and installation of the catalyst and any technical modifications made to the production process. This analysis assumes a capital cost of \$6.3/tonne of $HNO_3$ production capacity[3] and a plant capacity of 1,000 $tHNO_3$/day. Using these assumptions, the initial capital costs would equal \$2.3 million (2010 USD).

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[2] Based on costs of € 0.25/$tHNO_3$ reported in 2008 euros (EC, 2008) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI) and an exchange rate of 1.32 (USD/EUR).

[3] Based on costs of € 0.5/ $tHNO_3$ reported in 2008 euros (EC, 2008) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI) and an exchange rate of 1.32 (USD/EUR).

- **Annual O&M Costs:** Annual costs include catalyst replacement and recycling of spent catalyst; replacement of spare catalyst; loss of production due to catalyst disruptions or the lowering of the process pressure. This analysis assumes an annual cost of \$0.6/t$HNO_3$ produced and a plant utilization rate of 90% (Perez-Ramirez, 2003). Following the plant example of a 1,000 t$HNO_3$/day, the annual cost would be \$0.2 million (2010 USD).
- **Annual Benefits:** Minor benefits are associated with this option. Decomposition is an exothermic process, so a small amount of heat could be recovered from the process and converted to steam. However, the costs of the equipment needed to recover the heat and convert it to steam could outweigh the benefit. The ability to accrue benefits would also be limited by the amount of space available to add the equipment.
- **Applicability:** This option is applicable to most existing nitric acid plants but is highly dependent on site-specific factors, such as age of the facility and the footprint of the facility. Tertiary abatement measures may require additional space and additional equipment.
- **Technical Effectiveness:** The analysis assumes a 82% efficiency converting $N_2O$ into nitrogen and water.
- **Technical Lifetime:** 20 years

### IV.1.3.5 Nitric Acid—Tertiary Abatement Measure: Non-selective Catalytic Reduction (NSCR)

One specialized type of tertiary catalyst is an NSCR system. The NSCR typically costs more than other types of tertiary catalysts because it requires a reagent fuel, such as natural gas, propane, butane, or hydrogen, to reduce $NO_X$ and $N_2O$ over a catalyst. If an NSCR system is used at a nitric acid plant that is collocated with other chemical processes, the costs of these reagent fuels may be lessened. For example, if ammonia is produced near the nitric acid production plant, the waste gas stream from ammonia production is a hydrogen-rich gas stream that could be used as the reagent fuel for an NSCR.

- **Capital Costs:** Capital costs include the purchase and installation of the NSCR unit and catalyst. This analysis assumes a capital cost of \$12.6/tonne of $HNO_3$ production capacity based on \$8.2/t$HNO_3$ reported in 1991 USD (USEPA, 1991) scaled to 2010 USD using the Chemical Engineering Plant Cost Index (CEPI). Assuming a plant capacity of 1,000 t$HNO_3$/day, the initial capital cost would equal \$4.6 million (2010 USD).
- **Annual O&M Costs:** Annual costs total \$8.8/t$HNO_3$ produced. Annual costs include the cost of reagent fuel, labor, maintenance, and other fixed costs for capital recovery and insurance. Total annual cost for the example plant would be \$2.9 million per year (2010 USD).
- **Annual Benefits:** Energy benefits are associated with this option. The NSCR reaction is exothermic, which means that the reaction generates heat. This heat can be recovered and converted into steam for use as an energy source.
- **Applicability:** This option is applicable to all nitric acid production facilities without existing tertiary abatement measures. Although it is theoretically possible to employ multiple abatement measures, the likelihood of multiple retrofitted abatement measures operating together in an efficient manner is very low.
- **Technical Effectiveness:** The analysis assumes 90% efficiency converting $N_2O$ into nitrogen and water.
- **Technical Lifetime:** 20 years

## IV.1.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the $N_2O$ abatement measures for nitric and adipic acid production facilities.

### IV.1.4.1 Methodological Approach

The MAC analysis is based on project costs developed for a set of model facilities based on the abatement measure costs discussed in Section IV.1.3. Similar to the steps taken in other sectors, we developed an inventory of facilities that are representative of existing facilities. Next we applied the abatement costs to calculate the break-even prices for each option and applicable facility pair. Finally, the model estimates the mitigation potential based on the country-specific share of emissions attributed to nitric versus adipic acid production. This analysis takes the $N_2O$ emissions projections (given) and allocates emissions based on production process to derive the model facility inventories.

Adipic acid facilities are defined through a detailed inventory of the 23 production facilities worldwide operating in 2010. While no comprehensive inventory was available for nitric acid plants, it is believed that there are roughly 500 to 600 nitric acid plants globally (Kollmuss and Lazarus, 2010). Instead, we developed a series of 4 model nitric acid production units based on plant characteristics obtained from a detailed inventory of 67 nitric acid plants that varied in age and production processes.[4]

#### *Adipic Acid—Facility inventory*

The first step in the analysis was to determine the allocation of projected emissions to nitric and adipic acid production by country. For example, in the United States, adipic acid production accounted for approximately 15% of total baseline emissions in 2010, while the majority of emissions were attributed to nitric acid production. Once the share of baseline emissions is determined, the MAC model can assess the abatement potential on the technically applicable pool of emissions available for abatement.

To estimate the technically applicable share of emissions, we developed a detailed inventory of operational adipic acid plants in 2010. Adipic acid plants were used as the starting point because the number of international adipic acid plants is small (<30 globally), supported by recent literature providing detail on existing plants in 2010 obtained from Schneider, Lazarus, and Kollmuss (2010). The detailed inventory includes 23 adipic acid production facilities operating in 11 countries totaling approximately 3,000 kt of production capacity.[5] Schneider and co-authors also identified the $N_2O$ abatement technologies and plant utilization factors. Figure 1-4 summarizes the global adipic acid production capacity breakdown by country, and facility counts are reported in parenthesis after the country labels. The bottom-up inventory was used to estimate $N_2O$ emission from adipic acid production by country.

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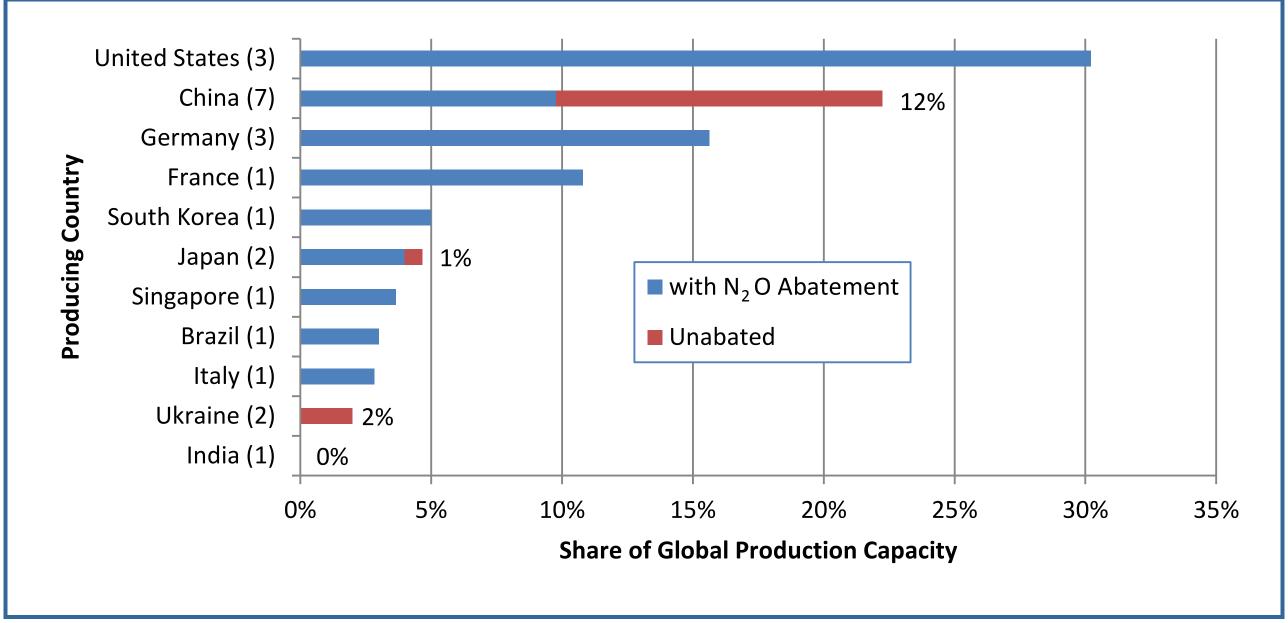
[4] While there are a number of different processes employed at nitric acid production facilities, single-pressure plants are much more common in the United States. Based on information gathered, most nitric acid production plants were constructed to maximize the yield from stages two and three of the production process and, therefore, operate at high pressures.

[5] Major changes to previously reported adipic acid inventories (Mainhardt and Kruger, 2000; Organisation for Economic Co-operation and Development [OECD], 2004) includes the opening of 5 new plants in China between 2008 and 2009; and the closure of two plants located in Canada and the United Kingdom. In addition, a fourth plant located in the United States was idle between 2008 and 2009 and assumed to continue to idle in 2010 (USEPA, 2012b).

**Figure 1-4: Operational Adipic Acid Production Facilities in 2010 by Share of Global Capacity**



Source: Adapted from Schneider et al. 2010.

Note: Facility counts are listed in parentheses beside country name.

Although 11 countries currently produce adipic acid, only 4 countries (China, Ukraine, Japan, and India) have operational facilities that are known to have no $N_2O$ emission controls in place. As the figure shows, all but 15% of the adipic acid capacity has $N_2O$ abatement controls in place. The 15% of capacity with no $N_2O$ abatement controls is represented by the nine smallest facilities in the industry located in China (5), Ukraine (2), Japan (1), and India (1).

In the 1990s, most of the adipic acid producers in developed countries voluntarily adopted $N_2O$ abatement measures (Schneider et al., 2010; EcoFys, 2009, USEPA, 2012b). In 2005, with the establishment of the CDM methodology for crediting $N_2O$ abatement projects at adipic acid plants, producers in developing countries began to adopt $N_2O$ abatement measures. Schneider and co-authors point out that although the CDM methodology was effective in achieving $N_2O$ reductions in developing countries, it was limited to facilities that were in operation prior to 2005.

Since 2005, much of the growth in adipic acid production capacity has been in China, with five plants coming online between 2008 and 2009 (Schneider et al., 2010). Future growth is also projected to be highly concentrated in Asia (Global Industry Analysts Inc. [GIA], 2010). China alone is expected to see its capacity more than double in the near term with five new adipic acid plants between 2011 and 2013 (Zhao, 2011).

Only 15% of global capacity continues to operate with no known $N_2O$ abatement. China and Ukraine account for over 95% of the capacity with unabated $N_2O$ emissions. In China, the five plants operating without abatement controls account for two-thirds of the country's total adipic acid capacity. For this analysis, we assume that future abatement potential is limited to the nine plants identified as having no known $N_2O$ abatement measure in place.

Although no information was available on specific plant utilization rates, we assume utilization rates of 60% for all non-CDM facilities, 85% for CDM facilities,[6] and 45% for non-CDM facilities in other parts of Asia (Schneider et al., 2011). Combining plant capacities and corresponding utilization rates yields a total adipic acid production in 2010 of 1.84 million metric tons.

Next we estimate net emissions for each country by applying the IPCC emissions factor of 300 kg $N_2O$ per metric ton of adipic acid produced to the plant production estimated above. Net emissions estimated account for existing abatement activity assuming a control efficiency of 96%. This analysis yields net emissions by country totaling 103,800 tonnes of $N_2O$ (32.2 $MtCO_2e$) in 2010.

We assume the net emissions calculated for each country represents adipic acid's representative share of total projected baseline emissions (see Table 1-2). Table 1-4 provides the percentages used to breakout the $N_2O$ emissions baseline to adipic acid.

The analysis assumes that $N_2O$ emissions from adipic acid production account for the percentage of total sectoral baseline listed in Table 1-4. We attribute the balance of baseline emissions to nitric acid production.

**Table 1-4: Adipic Acid-Producing Countries' Share of Baseline Emissions[a]**

| | Share of $N_2O$ Baseline, % | |
|---|---|---|
| **Country** | **Adipic Acid** | **Nitric Acid** |
| **Brazil** | 5 | 95 |
| **China[b]** | 36 | 64 |
| **France** | 30 | 70 |
| **Germany** | 21 | 79 |
| **India** | 1 | 99 |
| **Italy** | 27 | 73 |
| **Japan[b]** | 36 | 64 |
| **Singapore** | 25 | 75 |
| **South Korea** | 5 | 95 |
| **Ukraine[b]** | 36 | 64 |
| **United States** | 15 | 85 |
| **Other Countries** | 0 | 100 |

[a] For China, Japan, and Ukraine, the more detailed inventory-based estimate of emissions developed for this analysis yielded emission values greater than the total baseline projections for 2010. Hence, we defaulted back to percentages assumed for the previous report (36%).

[b] China, Japan, and Ukraine percentages used are from EMF 21 MAC model (USEPA, 2006).

### *Model Facility Description for Nitric Acid*

While it is believed that there are roughly 500 to 600 nitric acid plants globally (Kollmuss and Lazarus, 2010), no comprehensive inventory was available for nitric acid plants. Instead, we developed a series of 4 model nitric acid production units based on plant characteristics obtained from a detailed inventory of 67 nitric acid plants that varied in age and production processes. We organize the model facilities based on production capacity. All four facility types are assumed have an uncontrolled

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[6] Facilities located in Brazil, China, and South Korea.

emissions factor of 8.5 kg $N_2O$ per $tHNO_3$ produced[7] (IPCC, 2006). Table 1-5 summarizes the model facilities for nitric acid production by capacity and resulting annual $N_2O$ emissions.

**Table 1-5: Model Nitric Acid Facilities Assumptions**

| Model Plants | Production ($tHNO_3$/yr) | Annual $N_2O$ Emissions (uncontrolled) ($tN_2O$) |
|---|---|---|
| **Small** | 30,600 | 261 |
| **Medium** | 113,333 | 968 |
| **Large** | 226,667 | 1,936 |
| **Modern plant** | 340,000 | 2,904 |

### *Estimate Abatement Project Costs and Benefits*

Abatement measure costs and technical efficiencies were applied to each of the model facilities to estimate the break-even prices. Based on facility characteristics, we estimate the abatement project costs and calculated the break-even prices. Table 1-6 summarizes the break-even price calculation for nitric and adipic acid production facilities.

**Table 1-6: Example Break-Even Prices for $N_2O$ Abatement Measures**

| Abatement Option | Reduced Emissions ($MtCO_2e$) | Annualized Capital Costs ($/$tCO_2e$) | Annual Cost ($/$tCO_2e$) | Annual Revenue ($/$tCO_2e$) | Tax Benefit of Depreciation ($/$tCO_2e$) | Break Even Price ($/$tCO_2e$) |
|---|---|---|---|---|---|---|
| **Adipic Acid Production** | | | | | | |
| Thermal destruction | 9.2 | 0.22 | 1.15 | 1.12 | 0.04 | 0.21 |
| **Nitric Acid Production** | | | | | | |
| **Secondary Abatement—** Catalytic decomposition in the burner | 0.8 | 0.4 | 0.6 | 0.0 | 0.1 | 0.86 |
| **Tertiary Abatement—** Tailgas catalytic decomposition | 0.9 | 0.5 | 0.2 | 0.0 | 0.1 | 0.67 |
| **Tertiary Abatement—** NSCR unit | 0.9 | 1.0 | 3.3 | 0.0 | 0.2 | 4.19 |

Note: Break-even price assumes 10% discount rate and 40% tax rate.

Thermal destruction based on adipic acid production capacity of 75 kt $yr^{-1}$ and nitric acid options based on 328kt $HNO_3$ $yr^{-1}$ production capacity.

## IV.1.4.2 MAC Analysis Results

Global abatement potential of $N_2O$ emissions in nitric and adipic acid production is 78% of annual emissions. The majority of abatement potential is associated with nitric acid production because of the high degree of abatement already occurring at adipic acid facilities. Table 1-7 and Figure 1-5 present the MAC curve results for 2030 showing a cumulative reduction potential of 111 $MtCO_2e$.

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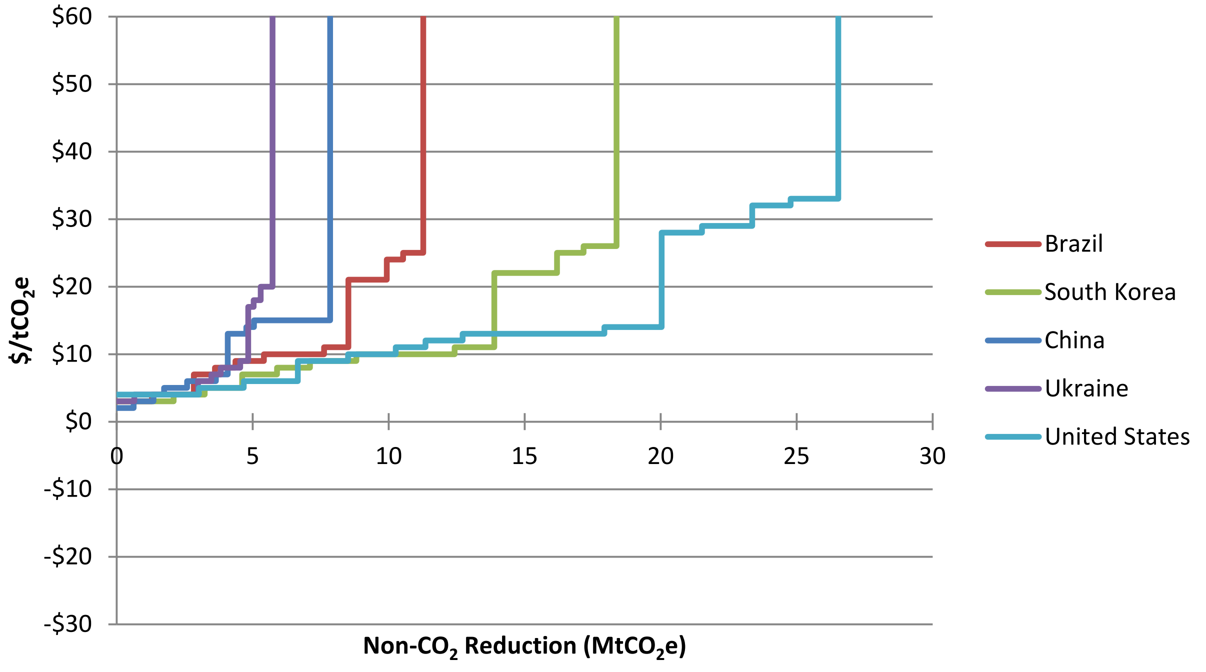
[7] The default emissions factor for the high pressure process is 9 kg $N_2O$ per ton of nitric acid; the default emissions factor for medium pressure processes is 7 kg $N_2O$ per ton of nitric acid produced.

### Table 1-7: Abatement Potential by Region at Selected Break-Even Prices in 2030

| | Break-Even Price ($/tCO$_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **−10** | **−5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| Brazil | — | — | — | 2.8 | 7.6 | 8.5 | 8.5 | 11.3 | 11.3 | 11.3 | 11.3 |
| China | — | — | — | 2.6 | 4.1 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 |
| South Korea | — | — | — | 4.6 | 12.4 | 13.9 | 13.9 | 18.4 | 18.4 | 18.4 | 18.4 |
| Ukraine | — | — | — | 3.0 | 4.8 | 4.8 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| United States | — | — | — | 4.7 | 10.3 | 20.0 | 20.0 | 23.4 | 26.5 | 26.5 | 26.5 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | 1.4 | 2.0 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| Central and South America | — | — | — | 0.3 | 0.9 | 1.0 | 1.1 | 1.3 | 1.3 | 1.3 | 1.3 |
| Middle East | — | — | — | 0.2 | 0.5 | 0.6 | 0.6 | 0.8 | 0.8 | 0.8 | 0.8 |
| Europe | — | — | — | 4.3 | 12.2 | 16.4 | 18.9 | 20.8 | 23.2 | 23.2 | 23.2 |
| Eurasia | — | — | — | 2.9 | 4.6 | 6.0 | 6.0 | 6.1 | 6.1 | 6.1 | 6.1 |
| Asia | — | — | — | 2.3 | 5.5 | 6.6 | 7.5 | 8.4 | 8.8 | 8.8 | 8.8 |
| North America | — | — | — | 0.6 | 1.3 | 2.3 | 2.4 | 2.8 | 3.1 | 3.1 | 3.1 |
| **World Total** | **0.0** | **0.0** | **0.0** | **29.6** | **66.3** | **90.8** | **95.1** | **109.6** | **115.8** | **115.8** | **115.8** |

Figure 1-5: Marginal Abatement Cost Curve for Top 5 Emitters in 2030



A majority of abatement potential spans over 30 nitric acid-producing countries, and only a small fraction of abatement potential associated with adipic acid production is limited to adipic acid plants in China, Ukraine, and India. Total reduction potential is achieved at break-even prices between $0 and $50/tCO$_2$e.

### IV.1.4.3 Uncertainties and Limitations

This analysis leverages new data from public sources to improve on the facility-level detail used in developing abatement project costs. In addition, we have incorporated a comprehensive international inventory of current adipic acid production facilities. However, additional date and detail would improve our abatement potential estimates.

- Abatement technology utilization rates: Active CDM and Joint Implementation (JI) abatement projects in this sector have reported $N_2O$ reduction efficiencies and utilization rates significantly higher than the default assumptions provided by the IPCC.
- Technology applicability across various nitric acid production processes and better understanding of how cost for abatement measures would vary with each process.
- Improved estimates of regional changes in production over the next 20 to 30 years. For example expected increases in Chinese adipic acid production capacity out to 2015, assuming no abatement measures are installed would have significant impacts on both emission projections and abatement potential in some countries.

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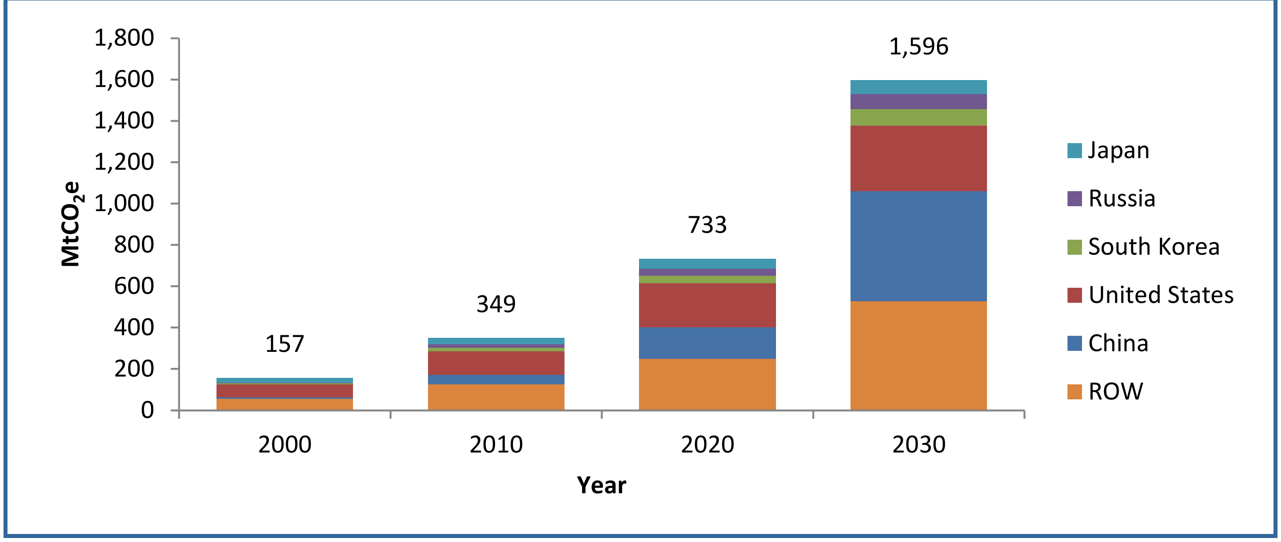
# IV.2. HFC Emissions from Refrigeration and Air Conditioning

## IV.2.1 Sector Summary

A number of hydrofluorocarbons (HFCs) are used in refrigeration and air conditioning (AC) systems and are emitted to the atmosphere during equipment operation, repair, and disposal, unless recovered, recycled and ultimately destroyed. The most common HFCs include HFC-134a, R-404A, R-410A, R-407C, and R-507A.[1] In response to the ozone depleting substance (ODS) phaseout, equipment is being retrofitted or replaced to use HFC-based substitutes or intermediate substitutes (e.g., hydrochlorofluorocarbons [HCFCs]) that will eventually need to be replaced by HFCs or other non-ozone-depleting alternatives. Greenhouse gas (GHG) emissions from the refrigeration/AC sector (excluding chlorofluorocarbons (CFCs) and HCFCs) were estimated at roughly 349 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010. By 2020, emissions from this sector are expected to reach 733 million $MtCO_2e$, as shown in Figure 2-1. A majority of the growth will result from increased use of HFCs in developing countries.

**Figure 2-1: HFC Emissions from Refrigeration and AC: 2000–2030 ($MtCO_2e$)**



Source: U.S. Environmental Protection Agency (USEPA), 2012.

This analysis reviews options to reduce emissions from the refrigeration/AC sector by using low-global warming potential (GWP) refrigerants, low-emission technologies, and improved practices to properly recover refrigerant at equipment servicing and disposal.

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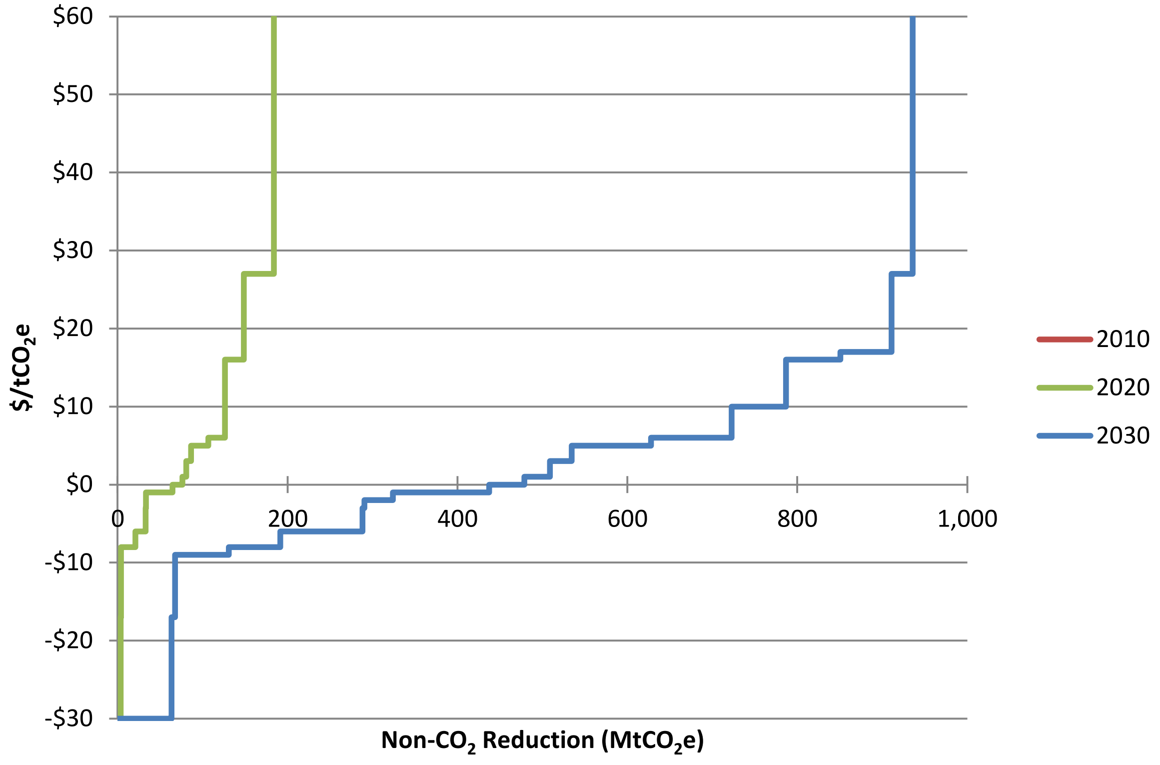
[1] R-404A, R-410A, R-407C, and R-507A refrigerant blends are composed of HFCs. Specifically, R-404A is 44% by weight HFC-125, 52% HFC-143a, and 4% HFC-134a,. R-410A is 50% HFC-32 and 50% HFC-134a. R-407C is 23% HFC-32, 25% HFC-125, and 52% HFC-134a. R-507A (also called R-507) is 50% HFC-125 and 50% HFC-143a.

Global abatement potential from refrigeration and AC in 2030 as evaluated in this analysis equates to approximately 70% of total annual emissions from refrigeration and AC end-uses and 28% of total emissions from ODS substitutes. In the near-term, abatement opportunities within refrigeration and AC are partially limited because many of the abatement options identified apply only to newly manufactured equipment and are thus limited by the turnover rate of the existing refrigeration and AC stock. In addition, this analysis does not explore new equipment abatement options for all refrigeration and AC equipment types, although such options may exist. Marginal abatement cost (MAC) curve results are presented in Figure 2-2. Maximum abatement potential of the options in the refrigeration and AC sector explored in this analysis is 540 $MtCO_2e$ in 2030. There are 317 $MtCO_2e$ of emissions reductions available in 2030 that are cost-effective at currently estimated prices.

**Figure 2-2: Global Abatement Potential in Refrigeration and AC: 2010, 2020, and 2030**



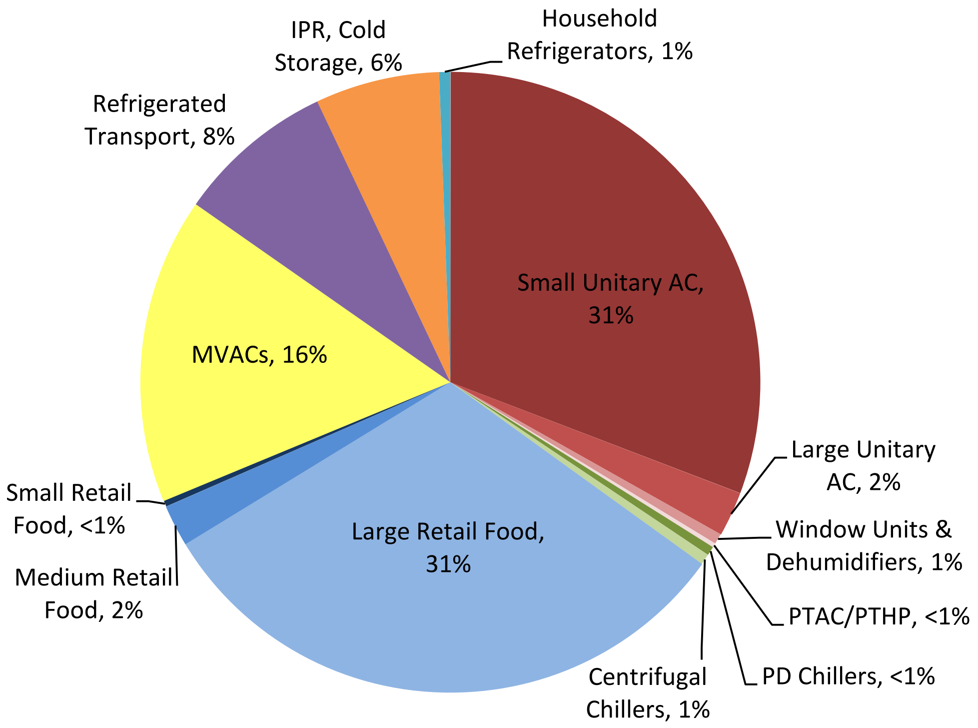
## IV.2.2 Emissions from Refrigeration and Air Conditioning

HFC emissions from refrigeration/AC occur during equipment manufacturing; as equipment is filled with coolant; during use, as a result of component failure, leaks, and purges; during servicing; and at the time of disposal, if the remaining refrigerant charge is not properly recovered. The use of refrigeration and AC equipment also generates indirect emissions of GHGs (primarily carbon dioxide) from the generation of power required to operate the equipment. HFC emissions can be reduced by adopting alternative technologies (that either reduce HFC leakage or substitute the refrigerant for a low/no GWP option) and by improving technician practices for equipment maintenance/servicing and disposal.

For the purpose of this analysis, the sector is characterized by six major end-use types, presented in descending order of 2020 GWP-weighted HFC emissions internationally (see Figure 2-3):

- *residential and commercial AC,* including window units and dehumidifiers, large and small unitary air conditioners (including both ducted and non-ducted split systems), centrifugal and positive displacement chillers, and packaged terminal air conditioners and packaged terminal heat pumps (PTAC/PTHP), used to regulate the temperature and reduce humidity in homes, apartment buildings, offices, hotels, shopping centers, and other large buildings, as well as in specialty applications such as ships, submarines, nuclear power plants, and other industrial applications;
- *retail food refrigeration*, including small commercial refrigerators/freezers; medium-sized condensing units found in convenience stores, restaurants, and other food service establishments; and large systems found in supermarkets;
- *motor vehicle air-conditioning (MVAC)* used in cars, trucks, and buses;
- *refrigerated transport*, including refrigerated vans/trucks, containers, ship holds, truck trailers, railway freight cars, and other shipping containers;
- *industrial process refrigeration (IPR)* and *cold storage warehouses,* including complex refrigeration systems used in the food/beverage production, chemical, petrochemical, pharmaceutical, oil and gas, metallurgical, and other industries as well as refrigeration systems used to cool meat, produce, dairy products, and other perishable goods that are in storage; and
- *household refrigerators and freezers* used primarily in residential buildings.

**Figure 2-3: Global HFC Emissions in 2020 by Application Type (% of GWP-Weighted Emissions)**



For the purpose of this analysis, the sector considers nine facilities and/or applications, as defined below.

- MVAC system used in a typical passenger car; for cost modeling purposes, this system is characterized as having a charge size of 0.77 kg of R-134a.
- Large retail food refrigeration system used in a typical supermarket (assumed 60,000 sq. ft.); for cost modeling purposes, this facility is characterized as having a charge size of 1,633 kg of R-404A.
- Small retail food equipment (e.g., stand-alone systems) typically used in supermarkets and convenience stores; for cost modeling purposes, this equipment is characterized as having a charge size of 0.5 kg of 90% R-134a and 10% R-404A (based on the average HFC refrigerant types currently installed in the U.S. market).
- Window AC unit or dehumidifier; for cost modeling purposes, this unit is characterized as having a charge size of 0.4 kg of R-410A.
- Unitary AC system or PTAC/PTHP; for cost modeling purposes, this system is characterized as having a charge size of 8 kg of R-410A.
- Positive displacement chiller (i.e., screw or scroll chiller); for cost modeling purposes, this equipment is characterized as having a charge size of 270 kg of 33% R-410A, 33% R-407C, and 33% R-134a (based on the average HFC refrigerant types currently installed in the U.S. market).
- IPR/cold storage system;[2] for cost modeling purposes, this system is characterized as having a charge size of 2,000 kg using 25% R-507A, 25% R-404A, 25% R-134a, and 25% R-410A (based on the average HFC refrigerant types currently installed in the U.S. market).
- Typical auto disposal yard using a recovery device to recover refrigerant from MVACs; for cost modeling purposes, this facility is characterized as recovering refrigerant from about 425 MVACs per year (with an average of 0.13 kg of R-134a recoverable per MVAC).
- Typical auto service shop using a recovery/recycling device to service MVACs; for cost modeling purposes, this facility is characterized as recovering refrigerant from about 150 MVACs per year (with an average 0.29 kg of R-134a recoverable per MVAC).

For modeling purposes, data typical for U.S. systems/equipment are used. Certain cost assumptions, such as labor rates, energy prices and capital costs, are adjusted for other regions.[3] Otherwise, it is assumed that the costs and reductions achieved in the United States can be scaled and are representative of the costs and reductions in other regions.

### IV.2.2.1 Activity Data or Important Sectoral or Regional Trends

Refrigeration/AC consumption, which is estimated using USEPA's Vintaging Model for the United States, is used to represent activity data. Consumption is assumed to scale with country gross domestic product (GDP). Regional differences are applied to other developed countries in the European Union

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[2] Abatement options for these types of equipment apply to only those facilities using HFCs. Many such facilities currently use ammonia and hence are not evaluated for further emission reductions in this analysis.

[3] In developing countries, it is assumed that capital costs are 10% higher, fuel prices are 30% higher, electricity costs are 66% higher, and labor costs are 20% lower than those relative to the United States.

(EU) to reflect higher consumption of low-GWP refrigerants in new passenger MVAC systems, domestic refrigerators, and large supermarket systems. For example, HCs have begun to penetrate the EU market in vending machines and other small retail food equipment (e.g., reach-in cases). Adjustments were also made to account for differences in the rates of ODS phaseout relative to the U.S. substitution scenarios.

### IV.2.2.2 Emission Estimates and Related Assumptions

Global emissions from refrigeration/AC were estimated at 349 $MtCO_2$ in 2010, projected to grow to 733 $MtCO_2$ by 2020 and 1,596 $MtCO_2$ by 2030. Table 2-1 presents the projected emissions from refrigeration/AC between 2010 and 2030. Growth in emissions is driven largely by GDP. Globally, HFC emissions from refrigeration/AC have been growing also because of the phaseout of ODS under the Montreal Protocol. Growth has also been driven by increased demand for air conditioning equipment, especially in emerging economies. Because of regulations associated with HFC-based refrigerants and/ or growing public pressure to transition away from such refrigerants, many developed countries have transitioned/are transitioning from ODS to natural refrigerants or other low-GWP alternatives in some end-uses. More detail on how HFC consumption and reduction potential of options are modeled is contained in Appendix D to this chapter.

**Table 2-1: Projected Baseline Emissions from Refrigeration and AC: 2010 to 2030 ($MtCO_2e$)**

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 45.8 | 82.7 | 151.2 | 328.8 | 534.1 | 13.1% |
| United States | 114.0 | 162.1 | 213.9 | 282.5 | 316.7 | 5.2% |
| South Korea | 17.0 | 24.5 | 35.7 | 61.1 | 79.7 | 8.0% |
| Russia | 16.0 | 23.2 | 33.4 | 56.0 | 72.0 | 7.8% |
| Japan | 30.9 | 38.7 | 48.0 | 62.0 | 66.7 | 3.9% |
| **Rest of Regions** | | | | | | |
| Africa | 12.5 | 18.7 | 28.1 | 49.3 | 64.9 | 8.6% |
| Central and South America | 16.2 | 23.4 | 34.3 | 59.5 | 78.2 | 8.2% |
| Middle East | 13.3 | 19.8 | 29.6 | 52.3 | 69.9 | 8.6% |
| Europe | 46.3 | 59.3 | 74.6 | 99.9 | 109.7 | 4.4% |
| Eurasia | 2.0 | 2.9 | 4.2 | 7.0 | 9.0 | 7.9% |
| Asia | 20.6 | 32.2 | 52.7 | 101.3 | 146.9 | 10.3% |
| North America | 14.8 | 20.4 | 27.4 | 40.4 | 48.1 | 6.1% |
| **World Total** | **349.3** | **507.9** | **733.1** | **1,199.9** | **1,596.1** | **7.9%** |

[a] CAGR = Compound Annual Growth Rate.

Source: U.S. Environmental Protection Agency (USEPA), 2012.

## IV.2.3 Abatement Measures and Engineering Cost Analysis

For the purpose of evaluating the cost of reducing HFC emissions from the refrigeration/AC sector, this analysis considers reduction costs for applying 14 new technologies and using three types of improved technician practices. Table 2-2 summarizes the technology and practice options reviewed and the types of equipment that are assumed to adopt such options, and the associated system type definitions (i.e., the equipment characteristics assumed in order to develop the option costs).

**Table 2-2: Refrigeration and AC Abatement Options**

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **Enhanced HFC-134a in MVACs** | 50% | New MVACs in light-duty vehicles |
| **HFO-1234yf in MVACs** | 99.7% | New MVACs in light-duty vehicles |
| **Enhanced HFO-1234yf in MVACs** | 99.8% | New MVACs in light-duty vehicles |
| **Distributed systems in large retail food** | 80% | New large retail food refrigeration systems |
| **HFC secondary loop and/or cascade systems in large retail food** | 94.6% | New large retail food refrigeration systems |
| **$NH_3$ or HC secondary loop and/or cascade systems in large retail food** | 100% | New large retail food refrigeration systems |
| **$CO_2$ Transcritical systems in large retail food** | 100% | New large retail food refrigeration systems |
| **Retrofits of R-404A systems in large retail food** | 46% | Existing large retail food refrigeration systems |
| **HCs in small retail food systems** | 100% | New small retail food refrigeration systems |
| **HC in window units and dehumidifiers** | 100% | New window AC units and dehumidifiers |
| **R-32 in unitary AC and PTAC/PTHP** | 75% | New unitary AC equipment and PTAC/PTHP |
| **MCHX in small and medium AC systems** | 37.5% | New unitary AC equipment |
| **R-32 with MCHX in unitary AC** | 84.5% | New unitary AC equipment |
| **MCHX in large AC systems** | 37.5% | New positive displacement chillers |
| **$NH_3$ or $CO_2$ in large refrigeration systems** | 100% | New IPR and cold storage systems |
| **Refrigerant recovery at disposal** | 85% | All existing refrigeration/AC reaching disposal |
| **Refrigerant recovery at servicing** | 95% | All small equipment (i.e., MVACs, small unitary AC) |
| **Leak repair** | 40% | All existing large equipment (i.e., large retail food, IPR, cold storage, and chillers) |

A number of these technology options have already begun penetrating certain markets, particularly in the EU, Japan, and several other developed countries. For example, using HCs in small retail food equipment is increasingly common for new equipment sold in the EU and Japanese markets. Likewise, use of alternative refrigerants in passenger MVAC systems has begun in the EU in response to Directive 2006/40/EC (the MAC Directive), which requires replacing HFC-134a with a refrigerant having a GWP of less than 150 in new model vehicles beginning in 2011 and in all new vehicles by 2017.[4] Alternative refrigerants are also increasingly being used in large supermarkets across Northern Europe and to a smaller extent in the United States, Canada, Australia, and other developed countries. The options of increased refrigerant recovery at service and disposal, as well as more rigorous leak repair for large

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[4] Due to supply problems of the refrigerant originally chosen by the MVAC industry (i.e., HFO-1234yf), the EU granted a 2-year dispensation to the auto industry. Additionally, some automobile OEMs have recently announced that they plan to continue to use HFC-134a refrigerant while they further investigate low-GWP options (EurActiv, 2013). Other OEMs have stated that they have not changed their plans to introduce HFO-1234yf and in fact some of these systems are already in operation today (*RAC Magazine*, 2013).

equipment, can bring significant emission savings, especially in developing countries, where they are less likely to be practiced in the baseline.

Each of the abatement options is described further in the sections below. Additional options considered but not yet included in the analysis are described in Sections IV.2.2.18 through IV.2.2.20. Several other options, not mentioned below, are also potentially available but have not been included in this analysis. All costs are presented in 2010 dollars based on the Consumer Price Index (U.S. Department of Labor, 2011).

### IV.2.3.1 Enhanced HFC-134a in New MVACs

This option reduces annual leak rates of HFC-134a MVAC systems by 50% through better system components, including improved system sealing, lower permeation hoses, improved fittings, and higher evaporator temperatures (USEPA and NHTSA, 2011). Enhanced HFC-134a systems are additionally assumed to reduce fuel consumption by an estimated 42% through improved component efficiency, improved refrigerant cycle controls, and reduced reheat of the cooled air (USEPA and NHTSA, 2011).

This option is applicable to a newly manufactured MVAC system in light duty vehicles[5] in all countries except the EU, where it is assumed to penetrate in the baseline. The one-time cost is estimated at roughly $73 per MVAC system—assumed to be 10% greater in developing countries. These costs are offset by annual savings that result from reduced fuel and refrigerant consumption (a combined savings of approximately $38 per system). In developing countries, fuel prices are assumed to be 30% greater, resulting in a combined savings of approximately $48 per system.

### IV.2.3.2 HFO-1234yf in New MVACs

HFO-1234yf has a GWP of only four and performs similarly to HFC-134a, making the use of current MVAC system designs with minimal changes feasible. HFO-1234yf is, however, slightly flammable (designated 2L flammability in Addendum h to ANSI-ASHRAE Standard 34-2010), which may necessitate certain safety mitigation strategies. This option has already begun penetrating the EU and U.S. markets in a couple models (*Refrigeration and Air Conditioning Magazine*, 2013). This option is assumed to be as efficient as conventional HFC-134a MVAC systems (Oko-Recherche et al., 2011; Koban, 2009).

This option is applicable to a newly manufactured MVAC system in a light-duty vehicle in all countries except the EU, where it is assumed to penetrate the baseline market. The one-time capital cost is estimated at approximately $59 per MVAC system, resulting from incremental refrigerant costs and hardware changes the latter of which is assumed to be 10% greater in developing countries. Annual costs are assumed to be approximately $8 per system associated with incremental refrigerant replacement costs.

### IV.2.3.3 Enhanced HFO-1234yf in New MVACs

As a newly developed technology, HFO-1234yf MVAC systems may cost more than those currently containing HFC-134a. Further, a lower global production of the chemical, combined with the additional processes needed to produce it, is expected to lead to an initially high price for the chemical, but this may decrease as production increases. Similar to the Enhanced HFC-134a option, this option explores HFO-

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[5] This category includes cars, pick-up trucks, minivans, and sport utility vehicles.

1234yf for use in new MVAC systems using improved system components to allow for 50% reduced refrigerant leakage and efficiency improvements of 42%.

This option is applied to a newly manufactured MVAC system in light-duty vehicles in all countries. The one-time cost is estimated at roughly $100 per MVAC system, resulting from incremental refrigerant costs and better system components—the latter of which is assumed to be 10% greater in developing countries. The assumed incremental cost of the refrigerant is lower for this option than the original HFO-1234yf option on the basis that, over time with mass production of the chemical and systems to use it, the price will drop. Given this as well as the assumed lower leak rate of this option, annual costs are assumed to be only approximately $2 per MVAC system. These costs are offset by annual savings that result from reduced fuel consumption, equaling roughly $37 per system. In developing countries, fuel prices are assumed to be 30% greater, resulting in a savings of almost $48 per system.

#### IV.2.3.4 Distributed Systems in New Large Retail Food

A distributed system consists of multiple compressors that are distributed throughout a retail food store (e.g., a supermarket), near the display cases they serve, and are connected by a water loop to a chiller or other type of equipment that rejects heat (e.g., a cooling tower) that is located on the roof or elsewhere outside the store. Because distributed systems have smaller refrigeration units distributed among the refrigerated and frozen food display cases, refrigerant charges for distributed systems can be smaller than the refrigerant charge used in a comparable traditional centralized direct expansion (DX) system. The reduction in original charge size of the system will reduce HFC consumption (at first fill) and reduce potential emissions at the end of the equipment's life. Additionally, because of the placement of the units, a distributed system can require less refrigerant tubing and fittings than DX systems, thereby reducing total HFC leaks during the useful lifetime of the equipment to an estimated 80% relative to conventional systems. However, distributed systems are estimated to be 5% less efficient than conventional HFC centralized DX systems (IPCC, 2005). This technology is already being implemented today in many developed countries.

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. In developed countries, one-time costs are estimated to be 5% more expensive than conventional HFC centralized DX systems (IPCC, 2005), equivalent to an incremental cost of about $9,100 per supermarket; these costs are estimated to be 10% greater in developing countries. Annual costs are estimated at nearly $3,700 per supermarket in developed countries due to higher electricity consumption; these annual electricity costs are estimated to be 66% greater in developing countries. At the same time, annual refrigerant savings (due to reduced leakage) are realized, totaling nearly $1,800 per supermarket.

#### IV.2.3.5 HFC Secondary Loop and/or Cascade Systems in New Large Retail Food

Secondary loop systems use two fluids: a primary refrigerant and a secondary fluid. The secondary fluid is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment. In supermarkets, secondary loop systems are also sometimes used in combination with a cascade system. Cascade designs consist of two independent refrigeration systems that share a common cascade heat exchanger. The heat exchanger acts as the low temperature refrigerant condenser and serves as the high temperature refrigerant evaporator. Each component of a cascade design uses a different refrigerant that is most suitable for the given temperature range, with $CO_2$ commonly used in the low temperature circuit and an HFC used as the refrigerant at the medium temperature phase (RTOC, 2011). Because the HFC refrigerant is contained in the machine room in a secondary loop system and is not required for use in the low temperature circuit of a cascade design, these systems require a significantly lower refrigerant charge and have lower leakage rates, resulting in approximately 90% less annual leakage. While historically these systems were less efficient than conventional DX systems, today these systems are found to be just as efficient as conventional DX systems, if not more so, due to simplified piping, newly designed circulating pumps, and fewer components (Wang et al., 2010; DelVentura, et al., 2007; SuperValu, 2012; WalMart, 2006; Hinde, Zha, and Lan, 2009).

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. The one-time cost in developed countries is estimated to be 17.5% more expensive than conventional DX systems (IPCC, 2005), equivalent to an incremental cost of nearly $32,000 per supermarket; this capital cost is estimated to be 10% greater in developing countries. Annual savings associated with reduced refrigerant leakage are estimated to equal almost $2,000 per supermarket. These systems are assumed to be equally as efficient as DX systems, so no costs or savings are associated with annual energy consumption.

### IV.2.3.6 $NH_3$ or HCs Secondary Loop and/or Cascade Systems in New Large Retail Food

Similar to the HFC secondary loop and/or cascade option, in this system a secondary fluid is cooled by a primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment. In some cases, the secondary loop system is also used in combination with a cascade design, which does not rely on any HFCs in the low temperature circuit. For this abatement option, the primary refrigerant is assumed to be ammonia ($NH_3$) or HCs, which have a GWP that is negligible. Ammonia is not used in conventional supermarket refrigeration systems because such a system could expose consumers to toxic and slightly flammable refrigerant. Similarly, HCs are not used due to their high flammability. However, using a secondary loop allows the primary refrigerant to be isolated to a mechanical room with controlled access to only those with specific training. Because ammonia/HC 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 DX systems and operate at reduced charges. In addition, these systems are conservatively assumed to be 5% more energy efficient than conventional DX systems, with some supermarkets reporting actual efficiency gains of 0.5% to 35% (Wang et al., 2010; SuperValu, 2012; Hydrocarbonconversions.com, 2011).

This abatement option is applied to a newly manufactured large retail food system in a large supermarket. The one-time cost in developed countries is estimated to be 25% greater than conventional DX systems (IPCC, 2005), equivalent to an incremental cost of roughly $45,600 per supermarket; this capital cost is estimated to be 10% greater in developing countries. Annual savings are estimated at roughly $5,900 due to both reduced energy consumption and refrigerant savings (due to avoided HFC refrigerant leaks). In developing countries, where electricity rates are assumed to be higher, annual savings are assumed to total more than $8,300.

### IV.2.3.7 $CO_2$ Transcritical Systems in New Large Retail Food

This option eliminates the use of HFCs in large retail food refrigeration systems through the use of $CO_2$ as the primary refrigerant in a transcritical cycle. $CO_2$ transcritical systems are similar to traditional centralized DX designs but must operate at high pressures to accommodate the low critical temperature of $CO_2$ (GTZ Proklima, 2008). As a result, special controls and component specifications must be incorporated into the system design, which often result in higher upfront costs (USEIA, 2012). Additionally, $CO_2$ transcritical systems operate most efficiently in cooler climates, performing an estimated 5% to 10% more efficiently than DX systems using an HFC refrigerant in regions with an average annual temperature below 50°F (*Supermarket News*, 2012). At the same time, due to a possible energy penalty, the use of $CO_2$ transcritical systems in warmer climates is currently considered less viable. Specifically, use of these systems is most widely accepted in areas where the maximum ambient temperature is frequently below 88°F (*ACHR News*, 2010), or where the average annual temperature is lower than 59°F (Hill PHOENIX, 2012). Today, it is estimated that over 1,300 $CO_2$ transcritical systems are currently in operation in Europe with installations as far south as Italy and Spain in addition to a handful of systems that have been installed in Canada (Shecco, 2012). Plans are also currently underway to deploy the technology in supermarkets in the United States.

This abatement option is assumed to be applied to a newly manufactured large retail food system in large supermarkets in cooler climates. One-time costs in developed countries are estimated to be 17.5% more expensive than conventional HFC centralized DX systems (Australian Green Cooling Council, 2008; R744.com, 2012), equivalent to an incremental cost of nearly $32,000 per supermarket; these capital costs are estimated to be 10% greater in developing countries. Annual savings are estimated at about $5,900 per supermarket, which result from both refrigerant savings (due to avoided HFC refrigerant leaks) that total approximately $2,200 per supermarket, and energy savings (due to increased efficiency), which total approximately $3,700 per supermarket. In developing countries, where electricity rates are assumed to be higher, annual savings are assumed to total more than $8,300.

### IV.2.3.8 Retrofits of R-404A in Large Retail Food

Retail food refrigeration systems containing R-404A, which have high charge sizes and annual leak rates, can be retrofitted with lower-GWP refrigerants, such as R-407A (with a GWP of 1,770), to reduce their annual climate impact. While some system retrofits will require little to no change to achieve the desired operational characteristics, others may need additional modifications, such as changing the orifice or TXV size to achieve the same efficiency. If proper system evaluation is performed and considerations are taken to ensure the continued reliability of the system, retrofitting can lead to system improvements as a result of recommissioning the equipment (e.g., due to properly setting up controls and system operating valves, which may have wandered from set-point due to lack of maintenance) (*ACHR News*, 2012). However, because such changes may have occurred during remodeling, when the refrigerant retrofit is assumed to occur, no change in energy efficiency due to the new refrigerant is assumed.

To perform a system retrofit, the entire system must be shut down and checks should be made for leaks throughout the system. Solenoid sealings must then be changed as well as the filter driers. After the entire system is evacuated, the replacement fluid is deposited into the system.

For cost modeling purposes, it is assumed that retrofits are performed on large retail food systems at about half-way through its useful lifetime (i.e., 7 years) at the same time retrofits or remodeling of cases are underway. The original R-404A charge size of 1,633 kg is assumed to be replaced with an equivalent amount of R-407A. The procedure is assumed to require 10 hours of a service technician’s time (5 hours for the medium temperature system and 5 hours for the low temperature system), all of which is assumed to cost a total of roughly $500 in developed countries and $100 in developing countries (based on technician labor rates). Since the composition of R-404A and R-407A are similar, the cost of the refrigerant is assumed to be the same. Therefore, no annual costs or savings are assumed for this option.

### IV.2.3.9 HCs in New Small Retail Food Refrigeration Systems

For small retail food equipment, this option explores the replacement of HFC-134a and R-404A with HCs. HCs, such as butane and propane, have negligible GWPs. Although safety issues associated with HC use in small equipment previously presented a barrier to their use, these issues can be addressed, making them a viable alternative to HFCs. International standards exist to evaluate and mitigate such safety issues. For example, although R-290 (propane) is flammable, it has been successfully implemented in some self-contained hermetic systems.

This option is applied to a newly manufactured small retail food refrigeration system (e.g., stand-alone equipment). No one-time costs are estimated because this option is cost neutral (Unilever, 2008). An annual savings of less than $1 per system is estimated to result from avoided HFC refrigerant costs.

### IV.2.3.10 HCs in New Window AC and Dehumidifiers

R-410A is widely used in window AC units and dehumidifiers, brought about by regulations phasing out HCFC-22, which was previously used. By replacing R-410A with HCs, such as propane (R-290), which is assumed to have a negligible GWP, significant emissions can be avoided. Two Chinese AC manufacturers have already commercialized room AC units using R-290. The R-290 AC designs achieve lower refrigerant charge sizes than is currently required by international standard (IEC 60335-2-240) and include additional safety features, such as a special compressor design and refrigerant leak alarm system. Mass production of the R-290 units started in 2009, for initial sale in Europe and China (GTZ-Proklima, 2009).

For cost modeling purposes, this option is applied to newly manufactured window AC units and dehumidifiers. This option is conservatively assumed to have no one-time costs even though there is indication that R-290 AC units can be produced more cheaply than R-410A units as a result of the better heat transfer properties and lower pressure drop of R-290, which allows for the use of narrower tubes in the condenser and evaporator (GTZ-Proklima, 2009). Annual savings are estimated based on the reduced cost of HC refrigerant replacement compared with R-410A—estimated to result in a savings of approximately $0.33 per unit.

### IV.2.3.11 R-32 in New Unitary AC Equipment and PTAC/PTHP

In this option, R-32,[6] a mildly flammable (category 2L in ANSI/ASHRAE Standard 34-2010) refrigerant with a GWP of 650, is used in new unitary AC equipment and PTAC/PTHP to replace R-410A, which has a GWP of 1,725. R-32 performs with a reduced charge volume ratio of 66% compared to R-410A (Xu et al., 2012). This reduced charge volume results in a 75% reduction of the direct global warming impact compared to the R-410A system. It is also reportedly 2% to 3% more energy efficient than R-410A (Pham and Sachs, 2010). The equipment used also has the potential to be downsized by up to 15%, which can decrease one-time costs by reducing the amount of materials used. R-32 AC products are already available in Japan and are to be launched in India in February 2013 (Daikin, 2012; Stanga, 2012). Manufacturers in Algeria, China, Thailand, and Indonesia also plan to transition to R-32 AC systems (Stanga, 2012).

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial and large commercial unitary AC) and PTAC/PTHP. The option is conservatively assumed to result in a one-time cost savings of approximately $30 per system, due to the reduced quantity of refrigerant required and lower cost of the alternative refrigerant. Additional savings may be realized through reduced material costs; however, there may also be costs associated with

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[6] R-32 is chosen here due to the availability of data. Other options are under development or being applied. For example, both Godrej in India and Gree in China are producing units with HC refrigerants (Godrej, 2012; Gree, 2012).

designing a system to use a mildly flammable refrigerant. Annual savings are associated with reduced refrigerant replacement costs, estimated at approximately $2.6 per system. Annual energy savings are also likely to be associated with this option but are not quantified in this analysis.

### IV.2.3.12 MCHX in New Unitary AC Equipment

This option explores the use of microchannel heat exchangers (MCHX) in unitary AC equipment using R-410A. MCHXs are a modification of conventional heat exchangers, which transfer heat in AC and refrigeration systems (e.g., for the rejection of heat from indoor cooled spaces to the outside ambient space). Because MCHXs transfer heat through a series of small tubes instead of a single or multiple large-diameter tubes, systems using them require between 35% and 40% less refrigerant to operate than those using conventional heat exchangers. Likewise, if average leak rates remain the same,[7] the actual amount of refrigerant emitted would be less. In addition, MCHX systems perform better and are more energy efficient than conventional systems. They also require smaller components, which results in reduced quantities of metals and other materials required per unit, although potential savings in material costs are not analyzed here. MCHXs are already used widely by multiple manufacturers in the automotive industry and in certain models of screw and scroll chillers.

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial, and large commercial unitary AC). One-time savings equal to roughly $27 are assumed due to the smaller refrigerant charge. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $2.30 per system.

### IV.2.3.13 R-32 with MCHX in New Unitary AC Equipment

Similar to the option described above, this option explores the use of MCHX in unitary AC equipment but with R-32 refrigerant (with a GWP of 650) in place of R-410A (with a GWP of 1,725). The use of the MCHX results in a refrigerant charge reduction of between 35% and 40% compared with conventional heat exchangers, while the use of R-32 refrigerant allows a further charge size reduction of 66% compared with R-410A. Combined, the reduced charge volume and GWP lead to a lower global warming impact of approximately 85%.

For cost modeling purposes, this option is applied to a newly manufactured unitary AC system (e.g., residential, small commercial, and large commercial unitary AC). One-time savings equal to roughly $46 are assumed as a result of the smaller refrigerant charge and lower cost of the alternative refrigerant. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $3.90 per system.

### IV.2.3.14 MCHX in New Positive Displacement Chillers

This option is assumed to be applicable in screw and scroll chillers. As explained above, MCHXs are a modification of conventional heat exchangers, which transfer heat in AC and refrigeration systems (e.g., for the rejection of heat from indoor cooled spaces to the outside ambient space). Because MCHXs transfer heat through a series of small tubes instead of a single or multiple large-diameter tubes, systems

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[7] For example, if average leak rates are dominated by failures or service errors that lead to a catastrophic (100%) loss, and the MCHX system has the same reliability, then average leak rates would be the same.

using them require between 35% and 40% less refrigerant than those using conventional heat exchangers. In addition, MCHX systems perform better and may be more energy efficient than conventional systems. MCHXs are already used widely by multiple manufacturers in the automotive industry and in certain models of screw and scroll chillers.

For cost modeling purposes, this option is applied to a newly manufactured positive displacement chiller. One-time savings equal to nearly $900 are assumed due to the smaller refrigerant charge. No annual costs are assumed for this option. The annual savings associated with avoided refrigerant losses is estimated at approximately $50 per chiller.

### IV.2.3.15 $NH_3$ or $CO_2$ in New IPR and Cold Storage Systems

This abatement option is assumed to be applicable to cold storage and industrial process refrigeration systems. Although $NH_3$ refrigeration systems are already common in refrigerated spaces over 200,000 sq. ft., additional penetration of $NH_3$ systems is possible in facilities that are less than 200,000 sq. ft. but greater than 50,000 sq. ft. In addition, modern $NH_3$ absorption refrigeration units are compact, lightweight, efficient, economical, and safe, which has made more applications possible. Improved technologies have also expanded the technical feasibility of using $CO_2$ systems. $CO_2$ systems are being used in low-temperature refrigeration (−30°C to −56°C), while ammonia/$CO_2$ systems can be used for higher temperature refrigeration (−35°C to −54°C). The lower temperature for both systems is limited primarily by the −56°C triple point of $CO_2$ being used on the low side. The choice between these systems is primarily due to outdoor temperatures; in colder climates, a $CO_2$ system is both energy efficient and simpler, while in hotter climates a cascade system may be needed to maintain energy efficiency. In Europe and the United States, storage and production facilities have been built with ammonia/$CO_2$ cascade systems. These systems are estimated to be 2% to 20% more energy efficient compared with their HFC counterparts (Gooseff and Horton, 2008).

For cost modeling purposes, this option is applied to a newly constructed IPR/cold storage refrigeration system/facility. The incremental one-time cost is estimated at approximately $210,700 per system in developed countries (Gooseff and Horton, 2008), assumed to be 10% more in developing countries. The annual savings of approximately $50,300 per system is associated with lower refrigerant replacement costs and reduced energy consumption of 11%; annual electricity cost savings are assumed to be 66% greater for developing countries, resulting in annual savings of approximately $83,100.

### IV.2.3.16 Refrigerant Recovery at Disposal for All Existing Equipment Types

Some level of refrigerant recovery at equipment disposal already occurs in the baseline of developed and developing countries, because it is illegal to vent HFCs when equipment is discarded in the U.S. and elsewhere. However, this option explores more widespread, thorough efforts to recover refrigerant at disposal across all equipment types. The approach involves using a refrigerant recovery device that transfers refrigerant into an external storage container prior to disposal of the equipment. Once the recovery process is complete, the refrigerant contained in the storage container may be cleaned by using recycling devices, sent to a reclamation facility to be purified,[8] or destroyed using approved technologies (e.g., incineration).

For cost modeling purposes, this option is applied to an auto dismantling facility assumed to use a single refrigerant recovery device that meets SAE J2788 standards to perform MVAC recovery jobs. The incremental one-time cost is estimated at approximately $2,025 per facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost is estimated to be 10% greater in developing countries. Annual costs are estimated at roughly $1,100 per auto dismantling facility for technician labor time and the purchase of new filters for the recovery device (ICF, 2008). In developing countries, technician labor costs are assumed to be one-fifth the cost of that in developed countries; therefore, annual costs are assumed to be about $240. The annual savings is estimated at about $440 per auto dismantling facility, based on the value of the recovered refrigerant for reclamation/reuse.

### IV.2.3.17 Refrigerant Recovery at Servicing for Existing Small Equipment

Similar to disposal recovery, this option assumes more widespread and thorough refrigerant recovery practices while servicing HFC refrigeration/AC systems. Because it is assumed that significant refrigerant is already recovered during servicing of large equipment, this abatement option is only applied to MVAC and small unitary AC systems.

For cost modeling purposes, this option is applied to a U.S. auto servicing facility assumed to perform MVAC servicing jobs using a recovery/recycling (recharge) device designed to meet the SAE J2788 standard. The incremental one-time cost is estimated at approximately $4,050 per servicing facility for the purchase of a refrigerant recovery device in developed countries (ICF, 2008); this cost is estimated to be 10% greater in developing countries. The annual cost is estimated at roughly $870 per auto servicing facility in developed countries for technician labor time and the purchase of new filters for the recovery device (ICF, 2008); in developing countries, technician labor costs are assumed to be one-fifth the cost of that in developed countries; therefore, the annual cost is assumed to be nearly $194. The annual savings is estimated at roughly $350 per auto servicing facility, based on the value of the recovered refrigerant for reclamation/reuse.

### IV.2.3.18 Leak Repair for Existing Large Equipment

This abatement option is assumed to be applicable to large retail food, cold storage and industrial refrigeration, and positive displacement chiller systems. Some level of leak repair activity is already practiced in the baseline, but this option explores additional efforts to repair leaks.

For cost modeling purposes, this option is applied to large supermarkets requiring significant small repairs (e.g., maintenance of the purge system or replacement of a gasket or O-ring). A one-time cost of approximately $1,870 is estimated per supermarket for parts and labor needed to perform the repair in developed countries (USEPA, 1998); in developing countries, this cost is estimated to be 10% greater. The annual savings associated with avoided refrigerant replacement is estimated at $1,470 per supermarket.

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[8] 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, whereas reclamation requires sending the refrigerant off-site to a reclaimer.

#### IV.2.3.19 HCs in New Domestic Refrigeration Systems

HFC-134a may be replaced with HCs in household refrigerators. HCs, such as butane and propane, have very low GWPs of 4.0 and 3.3, respectively. The main disadvantage of HCs is that they are flammable, but engineering design changes and safety features in manufacturing plants have been successfully implemented to overcome these challenges. In 2009, roughly 40% of new household refrigerators/freezers produced globally contained HCs, with more than 400 million HC units in use worldwide (Greenpeace, 2009). This option is not quantitatively assessed in this analysis but will be considered for future updates.

#### IV.2.3.20 $CO_2$ in Transport Refrigeration

$CO_2$ is currently being used in trucks in cryogenic (open-loop) systems and is also viable for use in refrigerated ships and intermodal containers using a compressor system (Carrier, 2013; Environmental Leader, 2010). However, more sophisticated refrigeration cycles are needed for $CO_2$ systems to match the efficiency of equivalent HFC units under high ambient temperature operation. The cycle operation is often transcritical, which results in compressor discharge pressures up to five times higher than conventional HFC systems. Therefore, entirely new parts, design approaches, test procedures, service training, etc. are needed to design, build and operate a trans-critical $CO_2$ system (TEAP, 2011). Due to a lack of readily available cost information on this alternative, this option is not quantitatively assessed in this analysis.

#### IV.2.3.21 Low-GWP Refrigerants and Blends

Significant research and development (R&D) efforts are underway to identify feasible alternatives for high-GWP HFC refrigerants in multiple subsectors. For instance, the U.S. EPA’s Significant New Alternatives Policy (SNAP) program has found - 1233zd(E) (also called trans-1-chloro-3,3,3-trifluoroprop-1-ene) and HFO-1234ze(E) acceptable for use in chillers, used mainly for comfort AC in large residential and commercial buildings, including facilities with data processing and communication centers. Potential alternatives in numerous refrigeration and AC uses include ammonia, hydrocarbons, $CO_2$, water, HFC-32, and new low-GWP refrigerants such as HFO-1234yf, HFO-1234ze, -1233zd(E), and blends containing HFOs. The Air-Conditioning, Heating and Refrigeration Institute (AHRI) launched the Low-GWP Alternative Refrigerants Evaluation Program to evaluate low-GWP alternatives to HCFC-22, HFC-134a, R-404A, R-407C, and R-410A in various product types (AHRI, 2013). Some 40 chemicals were identified, including refrigerants or blends with no, low, and high flammability. The GWPs of these products also varied, from zero to about 1,300. Some of these blends are under intense development and testing and are most commonly known by trade names, including DR-5, DR-7, DR-33, L-20, L-40, L-41, N-13, N-40, and XP-10. Because of a lack of readily available cost information on this alternative, these options are not quantitatively assessed in this analysis.

### IV.2.4 Engineering Cost Data Summary

Table 2-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters.

Table 2-3: Engineering Cost Data on a Facility Basis

| Abatement Option/Facility Type | Project Lifetime (years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$)[a] |
|---|---|---|---|---|---|
| **Enhanced HFC-134a** | | | | | |
| MVAC—U.S./Other Developed, New | 12.0 | 73.2 | 37.9 | — | 0.1 |
| MVAC—EU, New | 12.0 | 73.2 | 37.9 | — | 0.1 |
| MVAC—Developing, New | 12.0 | 80.5 | 48.1 | — | 0.1 |
| **HFO-1234yf** | | | | | |
| MVAC—U.S./Other Developed, New | 12.0 | 59.1 | — | 7.9 | 0.2 |
| MVAC—EU, New | 12.0 | 59.1 | — | 7.9 | 0.2 |
| MVAC—Developing, New | 12.0 | 60.4 | — | 7.9 | 0.2 |
| **Enhanced HFO-1234yf** | | | | | |
| MVAC—U.S./Other Developed, New | 12.0 | 101.7 | 37.4 | 2.0 | 0.2 |
| MVAC—EU, New | 12.0 | 101.7 | 37.4 | 2.0 | 0.2 |
| MVAC—Developing, New | 12.0 | 109.0 | 47.5 | 2.0 | 0.2 |
| **Distributed Systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 15.0 | 9,117.3 | 1,763.7 | 3,684.0 | 656.6 |
| Large Retail Food—EU, New | 15.0 | 9,117.3 | 1,763.7 | 3,684.0 | 656.6 |
| Large Retail Food—Developing, New | 15.0 | 10,029.1 | 1,763.7 | 6,139.3 | 656.6 |
| **HFC Secondary Loop and/or Cascade Systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 15.0 | 31,910.6 | 1,984.1 | — | 784.9 |
| Large Retail Food—EU, New | 15.0 | 31,910.6 | 1,984.1 | — | 784.9 |
| Large Retail Food—Developing, New | 15.0 | 35,101.7 | 1,984.1 | — | 784.9 |
| **$NH_3$ or HC Secondary Loop and/or Cascade Systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 15.0 | 45,586.6 | 5,888.6 | — | 834.0 |
| Large Retail Food—EU, New | 15.0 | 45,586.6 | 5,888.6 | — | 834.0 |
| Large Retail Food—Developing, New | 15.0 | 50,145.3 | 8,343.9 | — | 834.0 |
| **$CO_2$ Transcritical Systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 15.0 | 31,910.6 | 5,888.6 | — | 834.0 |
| Large Retail Food—EU, New | 15.0 | 31,910.6 | 5,888.6 | — | 834.0 |
| Large Retail Food—Developing, New | 15.0 | 35,101.7 | 8,343.9 | — | 834.0 |
| **Retrofits of R-404A** | | | | | |
| Large Retail Food—U.S./Other Developed, Existing | 8.0 | 500.0 | — | — | 417.1 |
| Large Retail Food—EU, Existing | 8.0 | 500.0 | — | — | 417.1 |
| Large Retail Food—Developing, Existing | 8.0 | 100.0 | — | — | 417.1 |
| **HCs** | | | | | |
| Small Retail Food—U.S./Other Developed, New | 20.0 | — | 0.3 | — | 0.1 |
| Small Retail Food—EU, New | 20.0 | — | 0.3 | — | 0.1 |
| Small Retail Food—Developing, New | 20.0 | — | 0.3 | — | 0.1 |

(continued)

**Table 2-3: Engineering Cost Data on a Facility Basis (continued)**

| Abatement Option/Facility Type | Project Lifetime (years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$)[a] |
|---|---|---|---|---|---|
| **HCs** | | | | | |
| Window Units/Dehumidifiers—U.S./Other Developed, New | 11.5 | — | 0.3 | — | 0.1 |
| Window Units/Dehumidifiers—EU, New | 11.5 | — | 0.3 | — | 0.1 |
| Window Units/Dehumidifiers—Developing, New | 11.5 | — | 0.3 | — | 0.1 |
| **R-32** | | | | | |
| Unitary AC and PTAC/PTHP—Developed, New | 15.0 | −29.8 | 2.6 | — | 1.2 |
| Unitary AC and PTAC/PTHP—Developing, New | 15.0 | −29.8 | 2.6 | — | 1.2 |
| **MCHX** | | | | | |
| Unitary AC—Developed, New | 15.0 | −27.0 | 2.3 | — | 0.8 |
| Unitary AC—Developing, New | 15.0 | −27.0 | 2.3 | — | 0.8 |
| **R-32 with MCHX** | | | | | |
| Unitary AC—Developed, New | 15.0 | −45.7 | 3.9 | — | 1.3 |
| Unitary AC—Developing, New | 15.0 | −45.7 | 3.9 | — | 1.3 |
| **MCHX** | | | | | |
| Positive Displacement Chiller—Developed, New | 20.0 | −877.5 | 52.7 | — | 11.3 |
| Positive Displacement Chiller—Developing, New | 20.0 | −877.5 | 52.7 | — | 11.3 |
| **$NH_3$ or $CO_2$** | | | | | |
| IPR/Cold Storage—Developed, New | 25.0 | 210,659.6 | 50,228.1 | — | 258.8 |
| IPR/Cold Storage—Developing, New | 25.0 | 231,725.6 | 83,121.0 | — | 258.8 |
| **Recovery at Disposal** | | | | | |
| Auto Disposal Yard—U.S./Other Developed | 7.0 | 2,025.6 | 443.3 | 1,083.8 | 72.0 |
| Auto Disposal Yard—EU | 7.0 | 2,025.6 | 443.3 | 1,083.8 | 72.0 |
| Auto Disposal Yard—Developing | 7.0 | 2,228.1 | 443.3 | 237.0 | 72.0 |
| **Recovery at Servicing** | | | | | |
| Auto servicing station—U.S./Other Developed | 7.0 | 4,051.1 | 351.1 | 869.5 | 57.1 |
| Auto servicing station—EU | 7.0 | 4,051.1 | 351.1 | 869.5 | 57.1 |
| Auto servicing station—Developing | 7.0 | 4,456.3 | 351.1 | 194.2 | 57.1 |
| **Leak Repair** | | | | | |
| Large Retail Food—U.S./Other Developed, Existing | 5.0 | 1,872.9 | 1,469.7 | — | 532.4 |
| Large Retail Food—EU, Existing | 5.0 | 1,872.9 | 1,469.7 | — | 532.4 |
| Large Retail Food—Developing, Existing | 5.0 | 2,060.2 | 1,469.7 | — | 532.4 |

[a] Emission reductions shown include only reductions associated with HFCs; they do not include indirect ($CO_2$) emissions associated with differences in energy consumption.

## IV.2.5 Marginal Abatement Costs Analysis

This section describes the methodological approach to the assessment of international abatement measures for refrigeration and air conditioning.

### IV.2.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities in the United States, developed countries, and developing countries. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline (that is, the HFC emissions from the traditional ODS industries) attributable to each representative type of equipment and the technical effectiveness for each technology in each facility or system.

### IV.2.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/region/equipment type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by facility in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time as systems are upgraded; market penetration is a modeled value that accounts for a number of elements, such as market choice, the turnover rate to replace existing banks of equipment that use HFCs, and the lifetime of refrigeration and air-conditioning equipment. Technical effectiveness figures do not account for indirect GHG impacts (i.e., increases or decreases in electricity or fuel consumption), which are accounted for in the cost analysis.[9] Table 2-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

**Table 2-4: Technical Effectiveness Summary**

| Facility/Abatement Option | Technical Applicability | Market Penetration Rate (2030)[a] | Reduction Efficiency | Technical Effectiveness (2030)[b] |
|---|---|---|---|---|
| **MVACs – U.S./Other Developed** | | | | |
| Enhanced HFC-134a | New systems | 0% | 50% | 0% |
| HFO-1234yf | | 0% | 99.7% | 36% |
| Enhanced HFO-1234yf | | 100% | 99.8% | 64% |
| **MVACs – EU** | | | | |
| Enhanced HFC-134a | New systems | 0% | 50% | 0% |
| HFO-1234yf | | 0% | 99.7% | 0% |
| Enhanced HFO-1234yf | | 100% | 99.8% | 32% |

(continued)

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[9] Indirect GHG emissions are not accounted for in the technical effectiveness calculations so that the analysis can show purely ODS substitute (e.g., HFC) emission reductions achievable. While it is recognized that indirect GHG emissions can be significant, the incremental differences of the options considered here compared to traditional HFC systems are expected to be relatively small. Such differences, to the extent data is available on such, are accounted for in the cost analyses.

### Table 2-4: Technical Effectiveness Summary (continued)

| Facility/Abatement Option | Technical Applicability | Market Penetration Rate (2030)[a] | Reduction Efficiency | Technical Effectiveness (2030)[b] |
|---|---|---|---|---|
| **MVACs –Developing** | | | | |
| Enhanced HFC-134a | New systems | 0% | 50% | 4% |
| HFO-1234yf | | 100% | 99.7% | 44% |
| Enhanced HFO-1234yf | | 0% | 99.8% | 0% |
| **Large Retail Food – U.S./Other Developed** | | | | |
| Distributed systems | New systems | 10% | 80% | 17% |
| HFC secondary loop and/or cascade systems | | 50% | 95% | 28% |
| $NH_3$ or HC secondary loop and/or cascade systems | | 20% | 100% | 13% |
| $CO_2$ transcritical systems | | 20% | 100% | 19% |
| Retrofits of R-404A | R-404A systems at or beyond average age | 100% | 46% | 1% |
| **Large Retail Food – EU** | | | | |
| Distributed systems | New systems | 0% | 80% | 10% |
| HFC secondary loop and/or cascade systems | | 0% | 95% | 16% |
| $NH_3$ or HC secondary loop and/or cascade systems | | 35% | 100% | 21% |
| $CO_2$ transcritical systems | | 60% | 100% | 47% |
| Retrofits of R-404A | R-404A systems at or beyond average age | 100% | 46% | 1% |
| **Large Retail Food – Developing** | | | | |
| Distributed systems | New systems | 30% | 80% | 15% |
| HFC secondary loop and/or cascade systems | | 37% | 95% | 16% |
| $NH_3$ or HC secondary loop and/or cascade systems | | 13% | 100% | 4% |
| $CO_2$ transcritical systems | | 20% | 100% | 8% |
| Retrofits of R-404A | R-404A systems at or beyond average age | 100% | 46% | 3% |
| **Small Retail Food – U.S./Other Developed** | | | | |
| HCs | New systems | 100% | 100% | 68% |
| **Small Retail Food – EU** | | | | |
| HCs | New systems | 100% | 100% | 62% |
| **Small Retail Food – Developing** | | | | |
| HCs | New systems | 100% | 100% | 27% |
| **Window AC Units and Dehumidifiers – U.S./Other Developed** | | | | |
| HCs | New systems | 34% | 100% | 3% |
| **Window AC Units and Dehumidifiers – EU** | | | | |
| HCs | New systems | 50% | 100% | 3% |

(continued)

Table 2-4: Technical Effectiveness Summary (continued)

| Facility/Abatement Option | Technical Applicability | Market Penetration Rate (2030)[a] | Reduction Efficiency | Technical Effectiveness (2030)[b] |
|---|---|---|---|---|
| **Window AC Units and Dehumidifiers – Developing** | | | | |
| HCs | New systems | 50% | 100% | 3% |
| **PTAC/PTHP - Developed** | | | | |
| R-32 | New systems | 100% | 75% | 22% |
| **PTAC/PTHP – Developing** | | | | |
| R-32 | New systems | 50% | 75% | 6% |
| **Unitary AC – Developed** | | | | |
| R-32 | New systems | 0% | 75% | 27% |
| MCHX | | 0% | 37.5% | 11% |
| R-32 with MCHX | | 100% | 84.5% | 23% |
| **Unitary AC – Developing** | | | | |
| R-32 | New systems | 50% | 75% | 8% |
| MCHX | | 50% | 37.5% | 12% |
| R-32 with MCHX | | 0% | 84.5% | 0% |
| **Large AC: PD Chillers – Developed** | | | | |
| MCHX | New systems | 100% | 37.5% | 20% |
| **Large AC: PD Chillers – Developing** | | | | |
| MCHX | New systems | 100% | 37.5% | 19% |
| **IPR & Cold Storage – Developed** | | | | |
| $NH_3$ or $CO_2$ | New systems | 40% | 100% | 21% |
| **IPR & Cold Storage – Developing** | | | | |
| $NH_3$ or $CO_2$ | New systems | 20% | 100% | 5% |
| **Cross-Cutting Practice Options – U.S/Other Developed** | | | | |
| Refrigerant recovery at disposal | Existing equipment | 100% | 85% | 39% |
| Refrigerant recovery at servicing (small equipment) | | 40% | 95% | 16% |
| Leak repair (large equipment) | | 100% | 40% | 64% |
| **Cross-Cutting Practice Options – EU** | | | | |
| Refrigerant recovery at disposal | Existing equipment | 100% | 85% | 65% |
| Refrigerant recovery at servicing (small equipment) | | 40% | 95% | 15% |
| Leak repair (large equipment) | | 100% | 40% | 84% |
| **Cross-Cutting Practice Options – Developing** | | | | |
| Refrigerant recovery at disposal | Existing equipment | 100% | 85% | 35% |
| Refrigerant recovery at servicing (small equipment) | | 40% | 95% | 20% |
| Leak repair (large equipment) | | 100% | 40% | 42% |

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in Appendix D to this chapter.

[b] Technical effectiveness figures represent the percentage of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts (i.e., increases or decreases in electricity or fuel consumption), which are accounted for in the cost analysis.

### IV.2.5.3 Estimating Abatement Project Costs and Benefits

Table 2-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for developed and developing countries. Additional details on the analyses can be found in Appendix D to this chapter.

**Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC**

| Abatement Option/Facility Type | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Enhanced HFC-134a** | | | | | |
| MVAC—U.S./Other Developed, New | 0.1 | 198.7 | −420.8 | 45.1 | −267.2 |
| MVAC—EU, New | 0.1 | 198.7 | −420.8 | 45.1 | −267.2 |
| MVAC—Developing, New | 0.1 | 218.6 | −533.8 | 49.6 | −364.8 |
| **HFO-1234yf** | | | | | |
| MVAC—U.S./Other Developed, New | 0.2 | 67.3 | 36.8 | 15.3 | 88.8 |
| MVAC—EU, New | 0.2 | 67.3 | 36.8 | 15.3 | 88.8 |
| MVAC—Developing, New | 0.2 | 68.7 | 36.8 | 15.6 | 89.9 |
| **Enhanced HFO-1234yf** | | | | | |
| MVAC—U.S./Other Developed, New | 0.2 | 115.5 | −164.2 | 26.2 | −74.9 |
| MVAC—EU, New | 0.2 | 115.5 | −164.2 | 26.2 | −74.9 |
| MVAC—Developing, New | 0.2 | 123.9 | −211.5 | 28.1 | −115.8 |
| **Distributed systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 656.6 | 3.0 | 2.9 | 0.6 | 5.4 |
| Large Retail Food—EU, New | 656.6 | 3.0 | 2.9 | 0.6 | 5.4 |
| Large Retail Food—Developing, New | 656.6 | 3.3 | 6.7 | 0.7 | 9.3 |
| **HFC secondary loop and/or cascade systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 784.9 | 8.9 | −2.5 | 1.8 | 4.6 |
| Large Retail Food—EU, New | 784.9 | 8.9 | −2.5 | 1.8 | 4.6 |
| Large Retail Food—Developing, New | 784.9 | 9.8 | −2.5 | 2.0 | 5.3 |
| **$NH_3$ or HC secondary loop and/or cascade systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 834.0 | 12.0 | −7.1 | 2.4 | 2.5 |
| Large Retail Food—EU, New | 834.0 | 12.0 | −7.1 | 2.4 | 2.5 |
| Large Retail Food—Developing, New | 834.0 | 13.2 | −10.0 | 2.7 | 0.5 |
| **$CO_2$ Transcritical systems** | | | | | |
| Large Retail Food—U.S./Other Developed, New | 834.0 | 8.4 | −7.1 | 1.7 | −0.4 |
| Large Retail Food—EU, New | 834.0 | 8.4 | −7.1 | 1.7 | −0.4 |
| Large Retail Food—Developing, New | 834.0 | 9.2 | −10.0 | 1.9 | −2.7 |

(continued)

## Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC (continued)

| Abatement Option/Facility Type | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($/$tCO_2e$) | Net Annual Cost ($/$tCO_2e$) | Tax Benefit of Depreciation ($/$tCO_2e$) | Break Even Price ($/$tCO_2e$) |
|---|---|---|---|---|---|
| **Retrofits of R-404A** | | | | | |
| Large Retail Food—U.S./Other Developed, Existing | 417.1 | 0.4 | — | 0.1 | 0.3 |
| Large Retail Food—EU, Existing | 417.1 | 0.4 | — | 0.1 | 0.3 |
| Large Retail Food—Developing, Existing | 417.1 | 0.1 | — | 0.0 | 0.1 |
| **HCs** | | | | | |
| Small Retail Food—U.S./Other Developed, New | 0.1 | — | −3.5 | — | −3.5 |
| Small Retail Food—EU, New | 0.1 | — | −3.5 | — | −3.5 |
| Small Retail Food—Developing, New | 0.1 | — | −3.5 | — | −3.5 |
| **HCs** | | | | | |
| Window Units/Dehumidifiers—U.S./Other Developed, New | 0.1 | — | −2.6 | — | −2.6 |
| Window Units/Dehumidifiers—EU, New | 0.1 | — | −2.6 | — | −2.6 |
| Window Units/ Dehumidifiers—Developing, New | 0.1 | — | −2.6 | — | −2.6 |
| **R-32** | | | | | |
| Unitary AC and PTAC/PTHP—Developed, New | 1.2 | −5.6 | −2.2 | −1.1 | −6.7 |
| Unitary AC and PTAC/PTHP—Developing, New | 1.2 | −5.6 | −2.2 | −1.1 | −6.7 |
| **MCHX** | | | | | |
| Unitary AC—Developed, New | 0.8 | −7.3 | −2.9 | −1.5 | −8.7 |
| Unitary AC—Developing, New | 0.8 | −7.3 | −2.9 | −1.5 | −8.7 |
| **R-410A to R-32** | | | | | |
| Unitary AC—Developed | 1.2 | −5.6 | −2.2 | −1.1 | −6.7 |
| Unitary AC—Developing | 1.2 | −5.6 | −2.2 | −1.1 | −6.7 |
| **R-32 with MCHX** | | | | | |
| Unitary AC—Developed | 1.3 | −7.6 | −3.0 | −1.5 | −9.1 |
| Unitary AC—Developing | 1.3 | −7.6 | −3.0 | −1.5 | −9.1 |
| **MCHX** | | | | | |
| Positive Displacement Chiller—Developed, New | 258.8 | 149.5 | −194.1 | 21.7 | −66.3 |
| Positive Displacement Chiller—Developing, New | 258.8 | 164.4 | −321.2 | 23.9 | −180.7 |
| **$NH_3$ or $CO_2$** | | | | | |
| IPR/Cold Storage—Developed, New | 258.8 | 149.5 | −194.1 | 21.7 | −66.3 |
| IPR/Cold Storage—Developing, New | 258.8 | 164.4 | −321.2 | 23.9 | −180.7 |
| **Recovery at disposal** | | | | | |
| Auto Disposal Yard—U.S./Other Developed | 72.0 | 9.6 | 8.9 | 2.7 | 15.8 |
| Auto Disposal Yard—EU | 72.0 | 9.6 | 8.9 | 2.7 | 15.8 |
| Auto Disposal Yard—Developing | 72.0 | 10.6 | −2.9 | 2.9 | 4.8 |

(continued)

**Table 2-5: Example Break-Even Prices for Abatement Measures in Refrigeration and AC (continued)**

| Abatement Option/Facility Type | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Recovery at servicing** | | | | | |
| Auto servicing station—U.S./Other Developed | 57.1 | 24.3 | 9.1 | 6.8 | 26.6 |
| Auto servicing station—EU | 57.1 | 24.3 | 9.1 | 6.8 | 26.6 |
| Auto servicing station—Developing | 57.1 | 26.7 | −2.8 | 7.4 | 16.5 |
| **Leak Repair** | | | | | |
| Large Retail Food—U.S./Other Developed, Existing | 532.4 | 1.5 | −2.8 | 0.5 | −1.7 |
| Large Retail Food—EU, Existing | 532.4 | 1.5 | −2.8 | 0.5 | −1.7 |
| Large Retail Food—Developing, Existing | 532.4 | 1.7 | −2.8 | 0.5 | −1.6 |

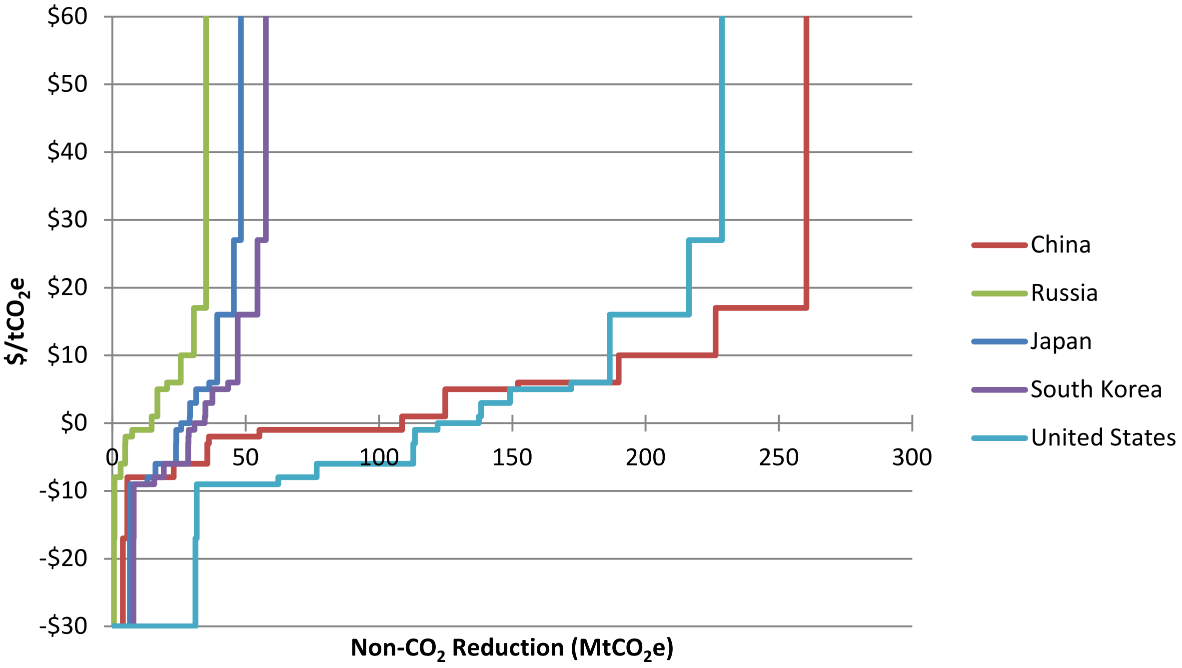
## IV.2.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 208 and 994 $MtCO_2e$, respectively. There are 479 $MtCO_2e$ of emissions reductions available in 2030 from implementing currently available technologies that are cost-effective at projected costs. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to users or manufacturers of refrigeration and AC systems, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 2-6 and Figure 2-4 by major country and regional grouping at select break-even prices in 2030.

**Table 2-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break-Even Price ($\$/tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **–10** | **–5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | 5.6 | 35.6 | 108.7 | 152.1 | 226.2 | 226.2 | 260.4 | 260.4 | 260.4 | 279.1 | 279.1 |
| Japan | 6.7 | 23.8 | 29.0 | 36.3 | 39.3 | 39.3 | 45.6 | 48.2 | 48.2 | 51.2 | 51.2 |
| Russia | 0.8 | 4.8 | 14.7 | 20.5 | 30.5 | 30.5 | 35.1 | 35.1 | 35.1 | 37.6 | 37.6 |
| South Korea | 8.0 | 28.4 | 34.6 | 43.3 | 47.0 | 47.0 | 54.5 | 57.6 | 57.6 | 61.2 | 61.2 |
| United States | 31.7 | 112.9 | 137.5 | 172.1 | 186.5 | 186.5 | 216.3 | 228.6 | 228.6 | 243.1 | 243.1 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | 0.7 | 4.3 | 13.2 | 18.5 | 27.5 | 27.5 | 31.6 | 31.6 | 31.6 | 33.9 | 33.9 |
| Central and South America | 1.0 | 5.9 | 16.5 | 22.9 | 33.5 | 33.5 | 38.6 | 38.7 | 38.7 | 41.5 | 41.5 |
| Middle East | 2.9 | 11.8 | 19.9 | 26.3 | 33.7 | 33.7 | 38.9 | 39.9 | 39.9 | 42.6 | 42.6 |
| Europe | 2.8 | 29.8 | 49.2 | 62.0 | 66.0 | 66.0 | 78.6 | 82.1 | 82.1 | 82.7 | 82.7 |
| Eurasia | 0.1 | 0.6 | 1.8 | 2.6 | 3.8 | 3.8 | 4.4 | 4.4 | 4.4 | 4.7 | 4.7 |
| Asia | 2.6 | 13.4 | 32.7 | 45.0 | 64.2 | 64.2 | 74.0 | 74.5 | 74.5 | 79.8 | 79.8 |
| North America | 4.8 | 17.2 | 20.9 | 26.2 | 28.4 | 28.4 | 32.9 | 34.8 | 34.8 | 37.0 | 37.0 |
| **Total** | **67.7** | **288.4** | **478.6** | **627.7** | **786.7** | **786.7** | **910.9** | **935.8** | **935.8** | **994.3** | **994.3** |

**Figure 2-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030**



## IV.2.6 Uncertainties and Limitations

The development of alternative refrigerants and technologies is quickly evolving in this sector, with efficiencies increasing and costs decreasing as research and market share expand. Thus, the costs and reduction efficiencies of the alternatives reviewed in this analysis are subject to change and likely very conservative. Moreover, new options not quantified in this analysis are entering the market and will continue to do so; additional options, such as HCs in domestic refrigerators, $CO_2$ in transport refrigeration, and low-GWP refrigerants for comfort cooling chillers, could be quantitatively considered in future analyses.

In addition, the costs for the options explored in this analysis are highly variable, depending on the types of systems reviewed. In particular, estimates of the amount of refrigerant recoverable from equipment at service and disposal are highly uncertain and highly variable based on the type of equipment. Recovery from large equipment is generally more cost-effective than for small equipment, because the amount of refrigerant recoverable is greater and the relative amount of technician time needed to perform the recovery is smaller. Similarly, 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 emission 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.

Finally, it is assumed that numerous abatement options result in increased or decreased energy consumption (e.g., enhanced HFO-1234yf or HFC-134a in MVACs, $CO_2$ transcritical large retail food refrigeration systems, distributed refrigeration systems, $NH_3$ or $CO_2$ in new IPR and cold storage systems). While the costs associated with the increase or decrease in energy consumption, which would vary widely based on region as well as particular application, is quantified as part of this analysis, the increase or decrease in $CO_2$ emissions associated with this energy use is not quantified. To accurately capture net emission reductions of these abatement options, emissions associated with the increase or decrease in energy use should also be calculated.

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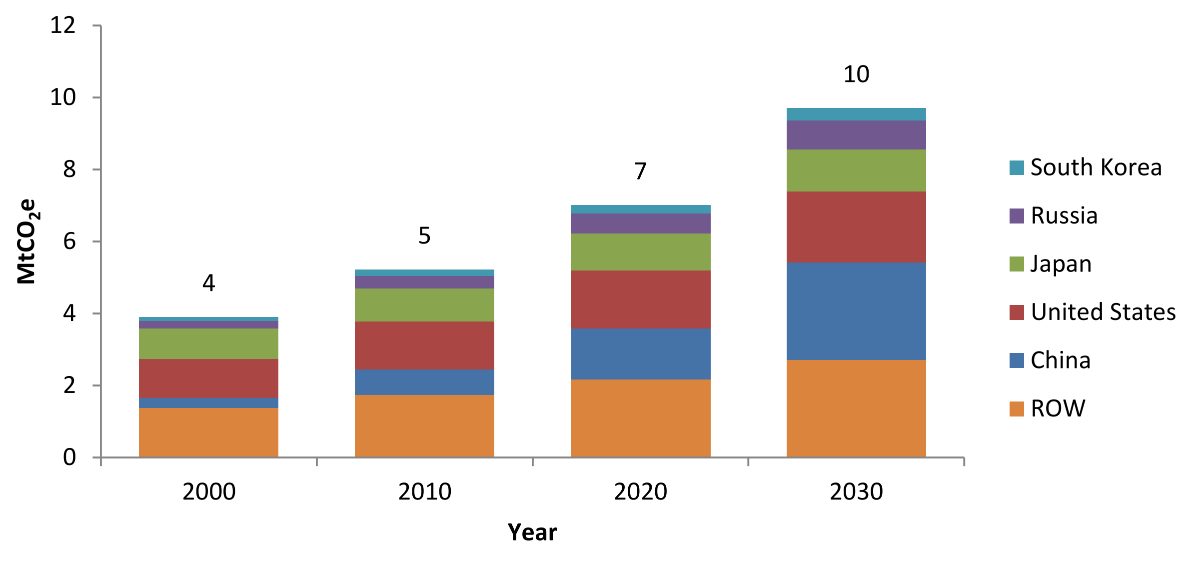
# IV.3. HFC Emissions from Solvent Use

## IV.3.1 Sector Summary

Historically, chlorofluorocarbons (CFCs) (in particular CFC-113), methyl chloroform, and, to a lesser extent, carbon tetrachloride were used as the predominant solvent cleaning agents. Hydrofluorocarbons (HFCs), hydrofluoroethers (HFEs), perfluorocarbons (PFCs), and aqueous and semi-aqueous not-in-kind (NIK) solvents have since replaced these historical solvents, with HFC emissions currently dominating the global warming potential (GWP)-weighted emissions from the solvents sector.

Greenhouse gas emissions from the solvents sector (excluding CFCs and HCFCs) were estimated at roughly 5 million metric tons of carbon dioxide equivalent ($MtCO_2e$.) in 2010. By 2030, emissions from this sector are expected to more than double, reaching over 10 $MtCO_2e$. A majority of the growth will result from increased use of HFCs in developing countries. Figure 3-1 presents the HFC and PFC baseline emissions from solvent use between 2000 and 2030.

**Figure 3-1: HFC and PFC Emissions from Solvent Use: 2000–2030 ($MtCO_2e$)**



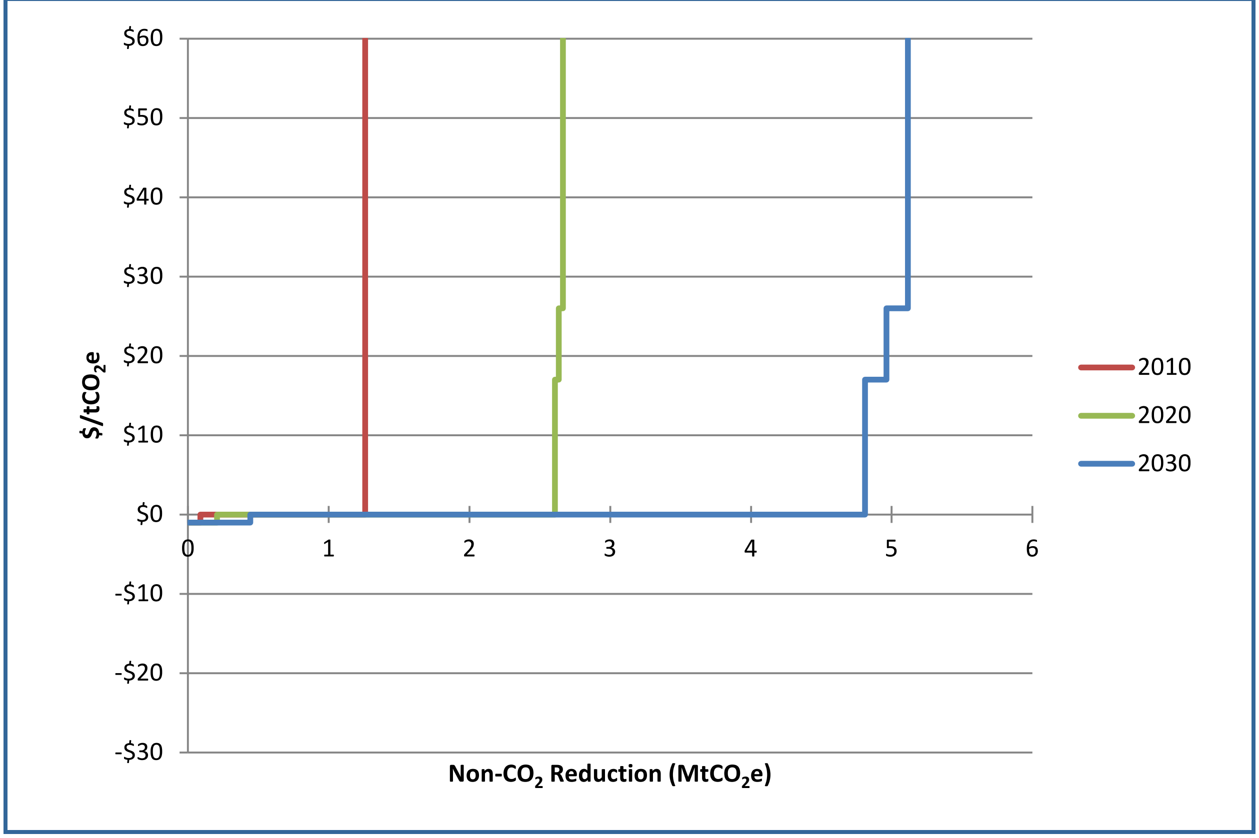
Source: U.S. Environmental Protection Agency (USEPA), 2012a

Four abatement options were identified for the solvent sector: (1) replacement of HFCs with HFEs, (2) retrofitting of equipment, (3) transition to NIK aqueous, and (4) transition to NIK semi-aqueous.

The global abatement potential is equal to approximately 58.9% of total annual emissions from the solvent sector and 0.3% of total annual emissions from all sectors that use ODS substitutes. These results are partly due to the assumed adoption of HFEs which, although they have a relatively lower GWP than HFCs, still result in emissions of greenhouse gases. In the same way, the adoption of equipment retrofits, another abatement option, still results in emissions of greenhouse gases. Finally, it is assumed that due to the performance limitations of the available alternatives, in the absence of policy measures, a portion of the market will not make the transition away from HFCs.

Marginal abatement cost (MAC) curve results are presented in Figure 3-2. Maximum abatement potential in the solvents sector is 5.7 $MtCO_2e$ in 2030. There are 4.8 $MtCO_2e$ of emissions reductions in 2030 that are cost-effective (i.e., $0/$tCO_2e$ or lower abatement cost) at currently projected energy prices.

**Figure 3-2: Global Abatement Potential in Solvent Use: 2010, 2020, and 2030**

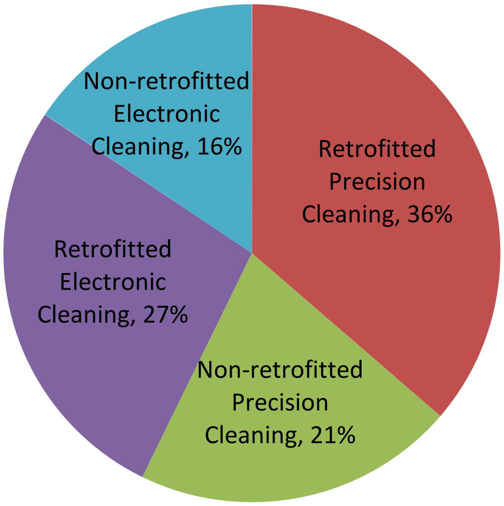


## IV.3.2 Emissions from Solvents

Although solvents are primarily an emissive use, emissions from solvent applications are not equal to the amount of solvent consumed in a year because a portion of used solvent remains in the liquid phase and is not emitted as gas during use. However, as the solvent is continuously reused through a distilling and cleaning process or through recycling, it is assumed that eventually approximately 90% of the solvent consumed in a given year is emitted, while 10% of solvent is disposed of with the sludge that remains.

For the purpose of this analysis, the sector is characterized by precision cleaning applications and electronics cleaning applications. Precision cleaning requires a high level of cleanliness to ensure the satisfactory performance of the product being cleaned, and electronics cleaning is defined as a process that removes contaminants, primarily solder flux residues, from electronics or circuit boards. To develop the cost analysis, the model vapor degreaser is assumed to be 10 square feet in size, uses HFC-4310mee as a solvent, and emits 250 to 500 pounds of solvent annually, depending on whether the equipment has been retrofitted. Figure 3-3 presents the global distribution of HFC and PFC emissions from solvent use in 2020 by degreaser type.

**Figure 3-3: Global HFC Emissions in 2020 by Degreaser Type (% of GWP-Weighted Emissions)**



### IV.3.2.1 Activity Data or Important Sectoral or Regional Trends

Solvent consumption, which is estimated using USEPA's Vintaging Model for the United States, is used to represent activity data. Solvent consumption is scaled according to country gross domestic product. Solvent emissions are directly correlated with solvent consumption; it is assumed that almost all (90%) of the solvent consumed in a given year is emitted. There are no regional differences in assumed emissions rates.

In developed countries, retrofits are assumed to have already been fully adopted, and in developing countries all equipment is assumed to remain nonretrofitted. In addition, although NIK replacement alternatives and HFE solvent applications currently exist worldwide, the baseline emissions considered here only covers that portion of the market still using HFCs and PFCs. Hence, for the purposes of transitioning away from the high GWP solvents in this analysis, there is no technology adoption of the NIK and HFE solvents in the baseline.

### IV.3.2.2 Emission Estimates and Related Assumptions

Global emissions of HFCs from the solvents sector were 5 $MtCO_2e$ in 2010, growing to 10 $MtCO_2e$ in 2030. Table 3-1 presents the projected emissions for solvents use by country and regions between 2010 and 2030. All emissions are the result of HFC-4310mee consumption.[1] Emissions are projected to grow significantly as developing country economies grow and demand for such solvents grows. Emissions were estimated based on assumptions about initial market size of the sector, the specific transitions away from CFCs and other ODSs in terms of timing and alternative solvent used, charge sizes, and leak rates, using the Vintaging Model.

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[1] PFC solvent use in precision cleaning end-uses is assumed to discontinue such that no emissions of PFCs are projected beyond 2010 from this sector.

**Table 3-1: Projected Baseline Emissions from Solvent Use: 2010–2030 ($MtCO_2e$)**

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 0.7 | 1.0 | 1.4 | 2.0 | 2.7 | 6.9% |
| United States | 1.3 | 1.5 | 1.6 | 1.8 | 2.0 | 2.0% |
| Japan | 0.9 | 1.0 | 1.0 | 1.1 | 1.2 | 1.2% |
| Russia | 0.4 | 0.4 | 0.5 | 0.7 | 0.8 | 4.2% |
| South Korea | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 3.5% |
| **Rest of Regions** | | | | | | |
| Africa | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 3.9% |
| Central & South America | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 3.3% |
| Middle East | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 3.8% |
| Europe | 1.1 | 1.1 | 1.2 | 1.3 | 1.4 | 1.2% |
| Eurasia | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.2% |
| Asia | 0.2 | 0.3 | 0.3 | 0.4 | 0.5 | 4.2% |
| North America | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 2.5% |
| **World Total** | **5.2** | **6.0** | **7.0** | **8.2** | **9.7** | **3.1%** |

[a] CAGR = Compound Annual Growth Rate

Source: USEPA, 2012a

## IV.3.3 Abatement Measures and Engineering Cost Analysis

A total of four abatement options were identified and analyzed for the solvent sector: (1) replacement of HFCs with HFEs, (2) retrofitting of equipment, (3) transition to NIK aqueous, and (4) transition to NIK semi-aqueous. Table 3-2 provides a technology overview of each abatement option.

Low-GWP alternatives for use in solvent applications are still emerging onto the market—perfluorobutyl iodide and Solstice 1233zd(E) are two such alternatives. The introduction of these substances involves regulatory approvals (such as the Significant New Alternatives Policy (SNAP) program evaluation process in the United States) followed by entry into the market and acceptance by users. These alternatives are discussed qualitatively in this chapter under "12.3.5 Low-GWP Alternatives."

**Table 3-2: Solvent Use Abatement Options**

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **HFC to HFE** | 76.4% | All facilities |
| **Retrofit** | 50% | Nonretrofitted facilities |
| **NIK aqueous** | 100% | Electronics cleaning |
| **NIK semi-aqueous** | 100% | Electronics cleaning |

### IV.3.3.1 HFC to HFE

This option, which is applicable to all facilities in the baseline, examines the replacement of HFC-4310mee with lower GWP HFE solvents. Although other low-GWP chemicals may be feasible, HFE-7100 and HFE-7200 are used as proxies for this abatement option because they display material compatibility properties similar to HFCs, a prime factor that has led to their success in the market. To model emission reductions, this option assumes that the degreaser transitions to the use of 75% HFE-7100 and 25% HFE-7200.[2] For the purpose of this analysis, the 100-year GWP of alternative solvents is calculated as the weighted average of 75% HFE-7100, with a GWP of 390, and 25% HFE-7200, with a GWP of 55, for a GWP of 306.25. The GWP of the solvent being replaced, HFC-4310mee, is 1,300;[3] thus, this option has a reduction efficiency of 76.4%.

Costs associated with the conversion to HFE solvents are assumed to be negligible because of similarities in key chemical properties of HFE solvents and HFC-4310mee, as well as similar pricing structures.

### IV.3.3.2 Retrofit

This abatement option is applicable to nonretrofitted facilities using solvents for the purpose of precision cleaning and electronics cleaning. Retrofits, including engineering control changes (e.g., increased freeboard height, installation of freeboard chillers, and use of automatic hoists), improved containment, and implementation of other abatement technologies can reduce emissions of HFCs used in solvent cleaning. Retrofitting a vapor degreaser, combined with proper operation and maintenance, can reduce solvent emissions from 46% to as much as 70%, depending on the specific retrofit methods chosen (Durkee, 1997). For example, installing a freeboard refrigeration device, sometimes referred to as a chiller (i.e., a set of secondary coils mounted in the freeboard), and maintaining a freeboard ratio of 1.0 to minimize diffusional solvent losses, can reduce emissions by 46%, while installing heating coils to produce superheated vapor along with installing a chiller can reduce emissions by 70%. For the purpose of this analysis, the reduction efficiency of the retrofit option is assumed to equal 50%.

In the United States, many enterprises have bought new equipment or retrofitted aging equipment into compliance with the National Emissions Standard for Hazardous Air Pollutants (NESHAP), which limits emissions from degreasers using traditional chlorinated solvents such as trichloroethylene. Fluorinated solvents such as HFCs are not covered by this regulation; nonetheless, a number of companies using HFCs and other nonchlorinated solvents have adopted NESHAP-compliant solvent cleaning machines because of the associated economic, occupational, and environmental benefits (i.e., reduced emissions) (Durkee, 1997). Likewise, many European countries have imposed stringent environmental and safety regulations that require the lowest level of emissions attainable by solvent degreasing equipment. Retrofit techniques were either already implemented or simply not required if the user had purchased new emission-tight vapor degreasers. Consequently, this analysis assumes that end

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[2] In actuality, a facility would choose one of the two HFEs for adoption; however, for modeling purposes this assumption was used to reflect the market presence of the two HFEs.

[3] Although the GWP value for HFC-4310mee was taken from the *IPCC Second Assessment Report* (1996), the report did not provide GWP values for either HFE. Consequently, this analysis uses the GWP values listed in the *IPCC Third Assessment Report* (2001) for both HFEs.

users in the United States and developed countries have already adopted these controls and that any emissions from these facilities cannot be further abated by this option. In contrast, solvent users in non-Annex I (i.e., developing) countries are assumed to not have retrofitted their equipment but may consider the equipment retrofit option, because updating their equipment may be preferred over investing in entirely new units.

Costs associated with adopting improved equipment and cleaning processes using existing solvents (retrofit) are incurred during the retrofit process and are estimated at $24,500 per degreaser. Annual savings of $4,500 are also realized through the avoided consumption of HFC that results from a reduction in emissions.

### IV.3.3.3 Not-in-Kind Aqueous

This abatement option is applicable only to facilities that use solvents for the purposes of electronics cleaning. This option replaces HFC-containing systems used for electronic cleaning end uses with an aqueous cleaning process. In the aqueous process, a water-based cleaning solution is used as the primary solvent and is usually combined with a detergent to remove contaminants. Because all HFCs are replaced with a solvent that does not have a GWP, the reduction efficiency of this option is 100%.

Costs associated with adopting an aqueous NIK replacement alternative are assumed to be $50,000 for the initial investment and $7,400 annually due to energy and water consumption costs. However, annual savings are also assumed to result from not using an HFC-based cleaner; savings are estimated to range from $6,700 to $11,200 depending on whether the solvent-based cleaning system had been retrofitted, which will significantly offset annual costs.

### IV.3.3.4 Not-in-Kind Semi-aqueous

This abatement option is applicable only to facilities that use solvents for the purposes of electronics cleaning. This option replaces HFC-containing systems used for electronic cleaning end uses with a semi-aqueous cleaning process. In the semi-aqueous process, the cleaning solution is an organic solvent that is blended with a surfactant, making it water soluble. An example of a solvent/surfactant blend is a terpene/water combination blended with glycol ethers. Because all HFCs are replaced with solvents that have no GWP, the reduction efficiency is 100%.

Costs associated with adopting a semi-aqueous NIK replacement alternative are assumed to be $55,000 for the initial investment and $9,100 annually due to energy and water consumption costs.[4] Annual savings are also assumed to result from not using an HFC-based cleaner; savings are estimated to range from $6,700 to $11,200 depending on whether the solvent-based cleaning system had been retrofitted.

### IV.3.3.5 Low-GWP Alternatives

Two low-GWP alternatives, perfluorobutyl iodide (PFBI) and Solstice 1233zd(E), are also emerging options. Both substances are new alternatives that may potentially abate HFC and HFE emissions in

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[4] Although these costs are higher than the NIK aqueous abatement option, it is assumed that the semi-aqueous option will nonetheless be adopted in some facilities, for example where the NIK aqueous option might not be effective for the particular cleaning required.

solvent cleaning; however, it is too soon to determine reasonable market penetration and costs associated with the transition to such options.

Solstice 1233zd(E) is a hydrochlorofluoro-olefin and is also referred to as trans-1-chloro-3,3,3-trifluoroprop-1-ene. Solstice 1233zd(E) is part of a new class of solvents specifically designed with a low atmospheric lifetime, ODP, and GWP, making it a candidate to replace high GWP HFCs and low or moderate GWP HFE solvents, as well as saturated HCFCs in solvent cleaning applications (UNEP, 2012). It has a GWP of 4.7 to 7 (USEPA, 2012b) and is nonflammable, making it an attractive option for some markets. The United States is completing its evaluation of whether it can be considered acceptable for use in electronics, precision, and metals cleaning.

PFBI also has a low GWP of 5. In 2012, PFBI was listed by the US Significant New Alternatives Policy (SNAP) program as acceptable for use in electronics, metal, and precision cleaning (USEPA, 2012c). This substance may be feasible for the cleaning oxygen systems in the aerospace industry as a potential replacement for HCFC-225ca/cb because of its good cleaning performance (Mitchell and Lowrey, 2012); however, it is unclear the extent to which this solvent will be used in place of HCFCs as well as HFC and HFE solvents.

Given the low GWP of these and similar options under development, we could expect emission reductions to be similar to the NIK aqueous and semi-aqueous options under the same market penetration assumptions. However, because these chemicals can also compete with HFEs with mid-range GWPs and could avoid the energy and water consumption barriers seen with the NIK options, market penetration may be further or faster than the options analyzed here.

### IV.3.3.6 Engineering Cost Data Summary

Table 3-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price. For more detailed costs see Appendix E.

**Table 3-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Facility Type | Project Lifetime (years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| **HFC to HFE** | Retrofitted | 15 | — | — | — | 113 |
| | Nonretrofitted | | | | | 136 |
| **Retrofit** | Nonretrofitted | 15 | $24,500 | $4,500 | — | 147 |
| **NIK aqueous** | Electronic/Retrofitted | 15 | $50,000 | $6,700 | $7,400 | 147 |
| | Electronic/Nonretrofitted | | | $11,200 | | 295 |
| **NIK semi-aqueous** | Electronic/Retrofitted | 15 | $55,000 | $6,700 | $9,100 | 147 |
| | Electronic/Nonretrofitted | | | $11,200 | | 295 |

## IV.3.4 Marginal Abatement Costs Analysis

This section describes the methodological approach to the international assessment of abatement measures for solvents.

### IV.3.4.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

### IV.3.4.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions from model facilities in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time as systems are upgraded and the options are applied in the future. Table 3-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

**Table 3-4: Technical Effectiveness Summary**

| Abatement Option | Technical Applicability | Market Penetration Rate (2030) | Reduction Efficiency | Technical Effectiveness |
|---|---|---|---|---|
| **Precision—retrofitted** | 60% | 100% | 76% | 46% |
| HFC to HFE | | | | |
| **Precision—nonretrofitted** | | | | |
| HFC to HFE | 60% | 80% | 76% | 37% |
| Retrofit | 100% | 20% | 50% | 10% |
| **Electronics—retrofitted** | | | | |
| HFC to HFE | 100% | 80% | 76% | 61% |
| Aqueous | 100% | 10% | 100% | 10% |
| Semi-aqueous | 100% | 10% | 100% | 10% |
| **Electronics—nonretrofitted** | | | | |
| HFC to HFE | 100% | 40% | 76% | 31% |
| Retrofit | 100% | 20% | 50% | 10% |
| Aqueous | 100% | 6% | 100% | 6% |
| Semi-aqueous | 100% | 6% | 100% | 6% |

### IV.3.4.3 Estimating Abatement Project Costs and Benefits

Table 3-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's monetary benefits equal to its costs. The previous section describes the assumptions used to estimate costs. The HFC to HFE option is available at no cost and represents 4.3 $MtCO_2e$ of reductions in 2030.

The break-even prices presented in Table 3-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors.

**Table 3-5: Example Break-Even Prices for Abatement Measures in Solvent Use**

| Abatement Option | Reduced Emissions (tCO$_2$e) | Annualized Capital Costs ($/tCO$_2$e) | Net Annual Cost ($/tCO$_2$e) | Tax Benefit of Depreciation ($/tCO$_2$e) | Break Even Price ($/tCO$_2$e) |
|---|---|---|---|---|---|
| **Precision—retrofitted** | | | | | |
| HFC to HFE | 113 | — | — | — | — |
| **Precision—nonretrofitted** | | | | | |
| HFC to HFE | 136 | — | — | — | — |
| Retrofit | 147 | 36.4 | −30.5 | 7.4 | −1.5 |
| **Electronics—retrofitted** | | | | | |
| HFC to HFE | 113 | — | — | — | — |
| Aqueous | 147 | 74.3 | 4.7 | 15.1 | 64.0 |
| Semi-aqueous | 147 | 81.8 | 16.3 | 16.6 | 81.4 |
| **Electronics—nonretrofitted** | | | | | |
| HFC to HFE | 136 | — | — | — | — |
| Retrofit | 147 | 36.4 | −30.5 | 7.4 | −1.5 |
| Aqueous | 295 | 37.2 | −12.9 | 7.5 | 16.7 |
| Semi-aqueous | 295 | 40.9 | −7.1 | 8.3 | 25.5 |

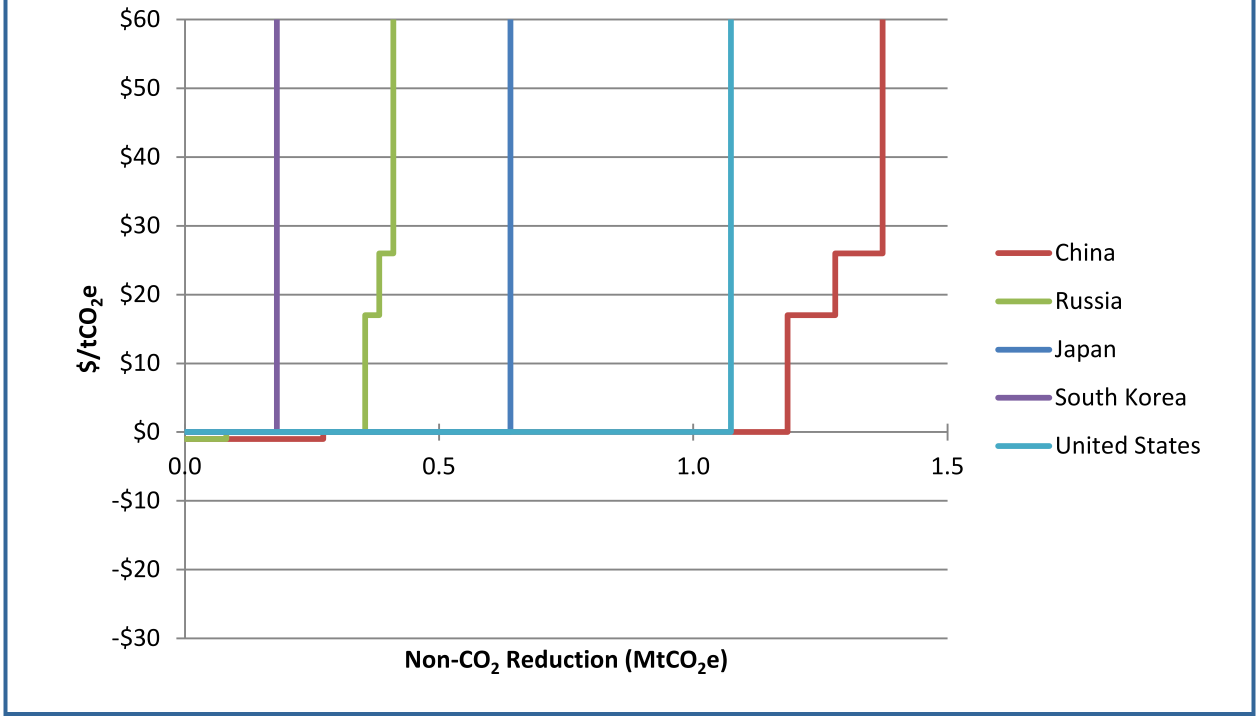
## IV.3.4.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 3.0 and 5.7 MtCO$_2$e, respectively. There are 4.8 MtCO$_2$e of reductions in 2030 resulting from implementing currently available technologies that are cost-effective at projected energy prices. The results of the MAC analysis are presented in Table 3-6 and Figure 3-4 by major country and regional grouping at select break-even prices in 2030.

**Table 3-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 (MtCO$_2$e)**

| | Break-Even Price ($/tCO$_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **–10** | **–5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | — | — | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 | 1.4 | 1.4 | 1.4 | 1.4 |
| Japan | — | — | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 0.8 |
| Russia | — | — | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| South Korea | — | — | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| United States | — | — | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.3 | 1.3 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Central and South America | — | — | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| Middle East | — | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Europe | — | — | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 |
| Eurasia | — | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Asia | — | — | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 |
| North America | — | — | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **World Total** | **—** | **—** | **4.8** | **4.8** | **4.8** | **4.8** | **5.0** | **5.1** | **5.1** | **5.7** | **5.7** |

**Figure 3-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030**



## IV.3.5 Uncertainties and Limitations

This analysis assumes that all developed countries have already adopted retrofitted equipment while all developing nations are still using nonretrofitted equipment. This is a very simplistic assumption that may not adequately reflect regional differences in the adoption of retrofitted equipment. Additionally, the reductions associated with adopting retrofitted equipment are based on older sources that may no longer be applicable to the current market. Further research in this area is needed to refine both baseline estimates and the reduction potential associated with retrofits.

Another area of uncertainty in this analysis is related to how costs for the mitigation technologies may vary internationally. The analysis is currently limited due to the lack of region-specific cost information.

Also, it is assumed that the aqueous and semi-aqueous abatement options result in increased energy consumption (3M, 2008); however, the increase in $CO_2$ emissions associated with this energy use is not quantified as part of this analysis. To accurately capture net emission reductions of these abatement options, emissions associated with the increased energy use should also be calculated.

Finally, low-GWP alternatives for use in solvent applications are still emerging onto the market and could potentially replace HFCs and HFEs, further reducing projected emissions once adopted. This analysis does not project further abatement that can occur because of these alternatives as information on their potential uptake by the market and associated transition costs is unknown at this time.

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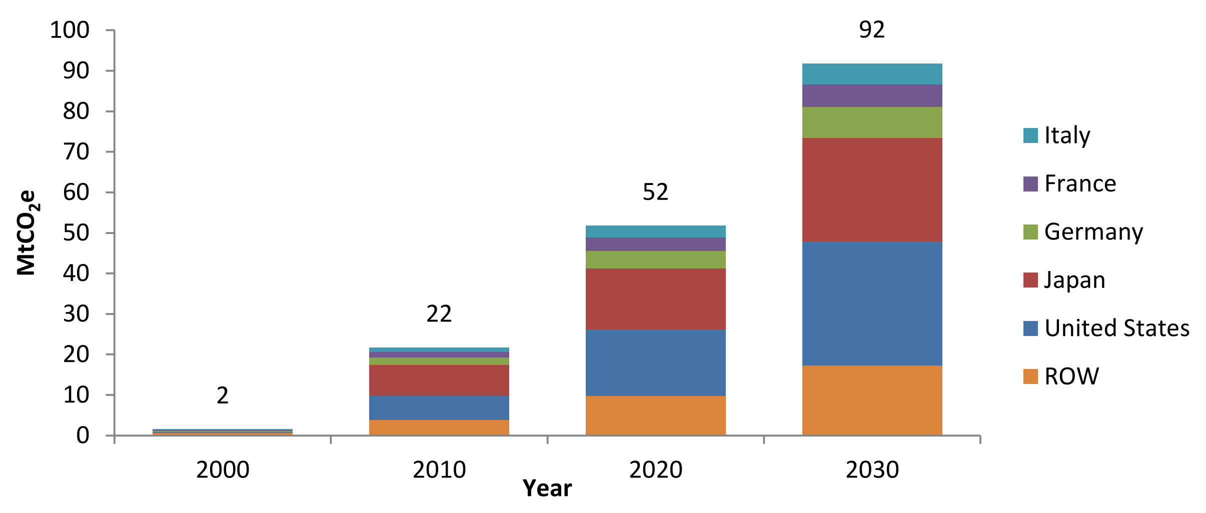
# IV.4. HFC Emissions from Foams Manufacturing

## IV.4.1 Sector Summary

Foam is used as insulation in a range of equipment and products, including refrigerated appliances, reefers and other refrigerated transport systems, in buildings (e.g., walls, roofs, floors) and pipes, and to produce other products, such as steering wheels, furniture, and shoes, for example. A wide variety of foam types are used for these applications, which have historically been produced with blowing agents that are ozone-depleting substances (i.e., chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons [HCFCs]), but since the ODS phaseout under the Montreal Protocol, HFCs have commonly been adopted in their place—primarily HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc. Greenhouse gas emissions from the foams sector (excluding CFCs and HCFCs) were estimated at roughly 22 million metric tons of carbon dioxide ($CO_2$) equivalent ($MtCO_2e$) in 2010. By 2020, emissions from this sector are expected to reach over 52 $MtCO_2e$, as shown in Figure 4-1.

**Figure 4-1: HFC Emissions from Foams Manufacturing: 2000–2030 ($MtCO_2e$)**

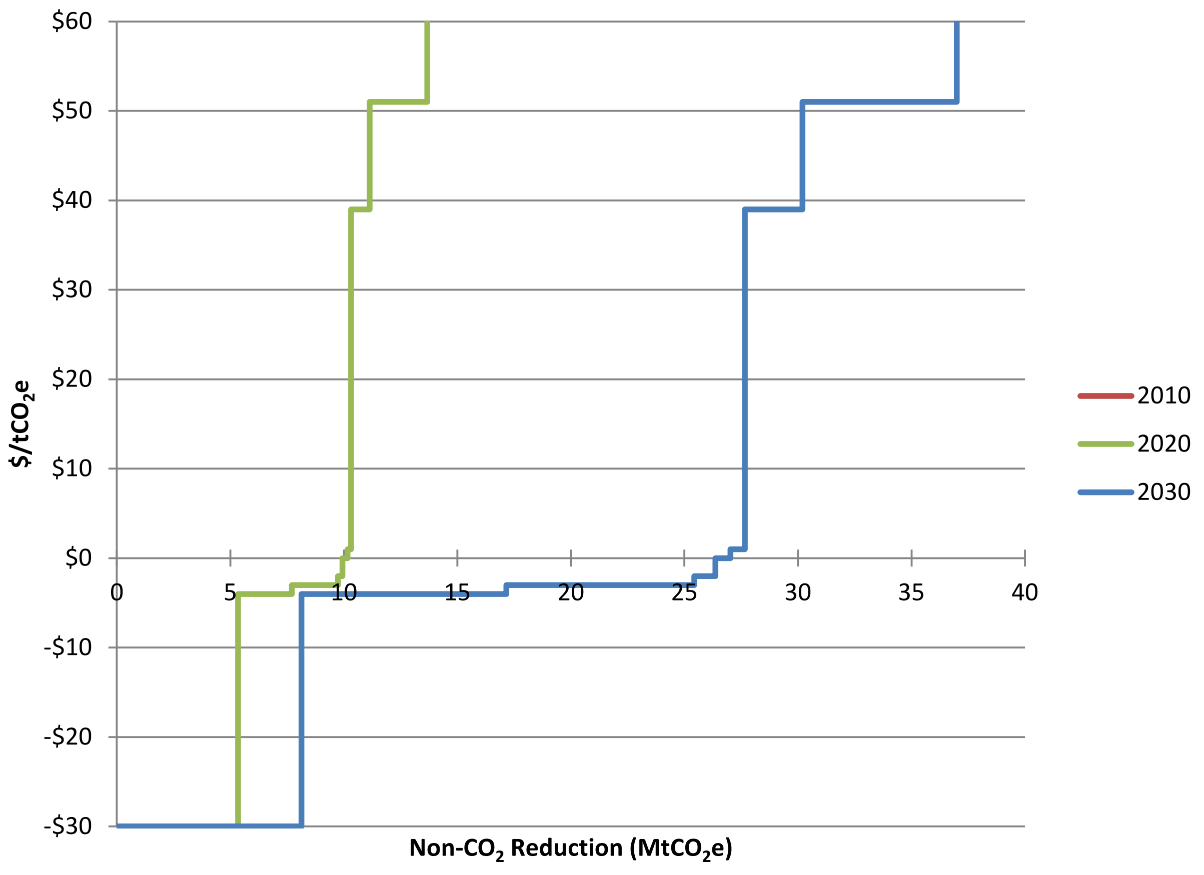


Source: USEPA, 2012a.

This analysis reviews options to reduce emissions from the foams sector by using low-global warming potential (GWP) foam-blowing agents in lieu of HFCs in new equipment/products and by recovering and destroying foam-blowing agents from household refrigerators at the end of the equipment's life.

Global abatement potential from the options reviewed equates to approximately 40.3% of total annual foam sector emissions and 21.9% of total emissions from ODS substitutes in 2030. While many options have been analyzed that can completely replace the HFC blowing agent in foams, abatement in the foams sector is limited by the lifetime of the installed base of foam products; all abatement opportunities analyzed replace the blowing agent in newly manufactured foams only, or destroy the blowing agent only at the foam natural end of life. Marginal abatement cost (MAC) curve results are presented in Figure 4-2. Maximum abatement potential in the foams sector is 37.0 $MtCO_2e$ in 2030. There are 27 $MtCO_2e$ of cost-effective emissions reductions in 2030, representing 29.4% of the foams baseline, based on the assumptions presented in this analysis. No reductions are available in 2010 as a result of the assumption that options did not start to penetrate the market until 2011.

Figure 4-2: Global Abatement Potential in Foams Manufacturing: 2010, 2020, and 2030



## IV.4.2 Emissions from Foams

Although there are two main types of foams—open cell and closed cell—HFCs are primarily used in closed-cell foam applications for their physical and performance properties.[1] HFC blowing agents are emitted during product/equipment manufacture, use, disposal, and even following disposal (e.g., in landfills) if the foam substance is not specially treated. For the purpose of evaluating the cost of reducing HFC emissions from this sector, this analysis considers emissions from the following closed-cell foam applications: polyurethane (PU) appliance foam, PU commercial refrigeration foam, extruded polystyrene (XPS) boardstock foam, PU continuous and discontinuous panel foam, PU one-component foam, and PU spray foam. The relative GWP-weighted emission shares of these applications in 2020 are shown in Figure 4-3.

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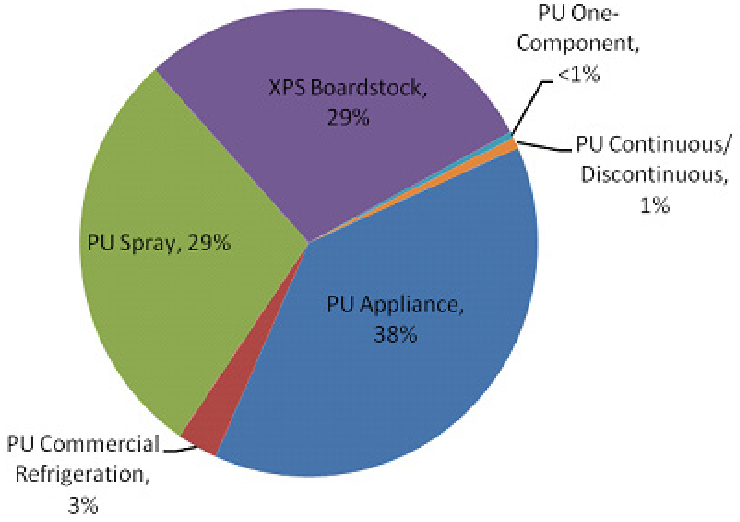
[1] Open cell foams experience significant blowing agent leakage due to the cell structure.

**Figure 4-3: Global HFC Emissions in 2020 by Application Type (% of GWP-Weighted Emissions)**



For the purpose of this analysis, the sector considers eight facilities and/or applications, as defined below.

- PU appliance foam manufacturing facility using HFC blowing agent: characterized as a typical manufacturing facility that produces 550,000 refrigerators per year and consumes nearly 537,000 kg of HFC-245fa blowing agent annually.
- PU commercial refrigeration foam manufacturing facility using HFC blowing agent: characterized as a typical manufacturing facility that produces 50,000 commercial units per year and consumes 70,000 kg of HFC-245fa blowing agent annually.
- PU spray foam contractor using HFC-245fa/$CO_2$ blowing agent: characterized as a typical PU spray foam contractor that uses nearly 58,000 kg of HFC-245fa/$CO_2$ PU spray foam annually.
- One-component foam manufacturing facility using HFC-134a or HFC-152a blowing agent: characterized as a typical facility that produces one-component foam and uses over 130,000 kg per year of HFC blowing agent.
- XPS boardstock production facility using HFC-134a/$CO_2$ blowing agent: characterized as a typical facility that creates approximately 1,000,000 board feet of XPS boardstock per year across 10 lines using nearly 7,100 kg of HFC-134a and $CO_2$ blowing agent.
- PU continuous and discontinuous foams manufacturing facility using HFC-134a blowing agent: characterized as a typical manufacturing facility that uses 453,000 kg of HFC-134a per year.
- Appliance demanufacturing facility using manual blowing agent recovery: characterized as a typical demanufacturing facility that manually processes 125,000 disposed domestic refrigerators per year.
- Appliance demanufacturing facility using fully automated blowing agent recovery: characterized as a typical demanufacturing facility that processes 200,000 domestic refrigerators per year using fully automated equipment.

For modeling purposes, data typical for facilities in the United States are used. Certain cost assumptions, such as capital costs, are adjusted for other regions.[2] Otherwise, it is assumed that the costs and reductions achieved in the modeled facilities could be scaled and would be representative of the costs and reductions in other regions.

### IV.4.2.1 Activity Data, Important Sectoral or Regional Trends and Related Assumptions

Foam consumption for the United States is estimated using the U.S. Environmental Protection Agency's (USEPA's) Vintaging Model. This consumption and associated emissions are assumed to scale with country gross domestic product (GDP), with several regional adjustments made to account for differences in HFC foam consumption based on data provided in FTOC (2010). Specifically, in the European Union, HFC consumption for XPS boardstock and commercial refrigeration is assumed to be lower than in the United States, because of a faster transition to low-GWP alternatives, while no HFC consumption is assumed in the PU appliance subsector (because the transition away from HFCs is already complete). Similarly, in developing countries, no HFC consumption is assumed in PU appliance, commercial refrigeration, XPS boardstock, PU spray, and PU continuous and discontinuous foams, because these subsectors are transitioning directly from ODS to non-HFC low-GWP alternatives. Additionally, a reduced proportion of HFC consumption in PU one-component foam is assumed in developing countries relative to the U.S. subsector (with consumption assumed only for HFC-134a, not HFC-152a).

### IV.4.2.2 Emission Estimates and Related Assumptions

Global HFC emissions from foams were estimated at 22 $MtCO_2e$ in 2010, projected to grow to 52 $MtCO_2e$ by 2020 and 92 $MtCO_2e$ by 2030. Growth in emissions is driven by GDP. Globally, HFC emissions from foam production and use have been growing because of the phaseout of ODS under the Montreal Protocol. Because of the costs associated with HFC-based foams, many countries have transitioned/are transitioning from ODS to hydrocarbons or other non-HFC alternatives. Because of developing countries' minimal use of HFCs, the growth in global emissions for the past decade has been driven by emissions from developed countries. Consumption is modeled based on USEPA's Vintaging Model, with emissions estimated based on assumed blowing agent loss rates at manufacture, during lifetime, and at disposal—which vary by foam application and blowing agent type. Emissions for major countries and regions are presented in Table 4-1.

## IV.4.3 Abatement Measures and Engineering Cost Analysis

This analysis considers the costs of reducing foam emissions by (1) replacing HFCs with low-GWP blowing agents in various types of foam manufacturing operations and (2) properly recovering and disposing of foam contained in the equipment at the end of its life. Specifically, eight abatement options were identified and analyzed for reducing emissions at product/equipment production by using hydrocarbon (HC) or $CO_2$ blowing agents in place of HFCs, and two options were identified for reducing

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[2] In developing countries, it is assumed that capital costs are 10% higher than those in the United States.

Table 4-1: Projected Baseline Emissions from Foams Manufacturing: 2010–2030 ($MtCO_2e$)

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| United States | 6.1 | 8.7 | 16.4 | 23.0 | 30.5 | 8.4% |
| Japan | 7.6 | 10.0 | 15.0 | 19.7 | 25.5 | 6.3% |
| Germany | 1.7 | 2.4 | 4.4 | 5.9 | 7.7 | 7.7% |
| France | 1.3 | 1.7 | 3.2 | 4.3 | 5.6 | 7.7% |
| Italy | 1.2 | 1.6 | 2.9 | 3.9 | 5.1 | 7.7% |
| **Rest of Regions** | | | | | | |
| Africa | — | — | — | — | — | 0.0% |
| Central & South America | — | — | — | — | — | 0.0% |
| Middle East | — | — | — | — | — | 0.0% |
| Europe | 3.0 | 4.1 | 7.7 | 10.2 | 13.4 | 7.7% |
| Eurasia | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 6.5% |
| Asia | 0.2 | 0.3 | 0.5 | 0.8 | 1.1 | 9.4% |
| North America | 0.5 | 0.7 | 1.3 | 1.8 | 2.4 | 8.4% |
| **World Total** | **21.7** | **29.6** | **51.8** | **70.0** | **91.8** | **7.5%** |

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA), 2012a.

emissions at the end of the equipment's life by using various methods of foam recovery at the time of appliance disposal. These options are described in the subsections below and summarized in Table 4-2. Additional details of the calculations are provided in Appendix F to this chapter.

Additional options considered, but not yet included in the cost analysis, are examined in Sections 4.3.11 through 4.3.13, after the 10 options listed in Table 4-2 are discussed. These and other options not mentioned are also potentially available but have not been included in this analysis due to data availability and time.

Table 4-2: Foams Manufacturing Abatement Options

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **Appliance: HFCs to HCs** | 100% | New PU appliances |
| **Commercial refrigeration: HFCs to HCs** | 100% | New PU commercial refrigeration units |
| **Spray: HFC245fa/$CO_2$ to HC** | 100% | New spray foam applications |
| **Spray: HFC245fa/$CO_2$ to $CO_2$** | 100% | New spray foam applications |
| **XPS: HFC134a/$CO_2$ to LCD/alcohol** | 100% | New XPS boardstock foam applications |
| **One component: HFC-134a to HCs** | 100% | New PU one-component foam applications |
| **One component: HFC-152a to HCs** | 100% | New PU one-component foam applications |
| **Continuous and discontinuous: HFC134a to HCs** | 100% | New PU continuous and discontinuous foam applications |
| **Appliance EOL: Manual process** | 85% | Domestic refrigerators reaching end of life |
| **Appliance EOL: Fully automated process** | 95% | Domestic refrigerators reaching end of life |

### IV.4.3.1 HCs in PU Appliances

This option replaces HFC-245fa used in PU appliance foam with HCs. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using HCs, including flammability, and lower insulation performance (USEPA, 2009), but these can be overcome through proper safety controls and engineering design. A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Approximately 50% of hydrocarbons used in appliances are based on cyclopentane and isopentane, due to their low operating costs and good foam properties (UNEP, 2010; TEAP, 2012). Cyclopentane has also been blended with isobutene to improve flow-ability and compressive strength, or with methylal, to improve performance (UNEP, 2010). Flammability, however, may cause a high incremental capital cost for facilities, which may be uneconomic for small or medium-sized enterprises; otherwise, HCs have low operating costs (TEAP, 2012). Using HCs instead of HFC-245fa in PU appliance foam eliminates HFC emissions at all stages of the product life cycle (i.e., at manufacturing, during appliance use, and at appliance disposal).

This option applies to HFC-245fa in newly manufactured PU appliance foam. This option is not applied in the European Union or in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at approximately $4.8 million per facility for safety modifications, installation/retrofit of high-pressure foam dispensers, installation of systems storage tanks, pumps, and premixing stations, as well as training, trials, testing, and certification (TEAP, 2012; UNEP, 2011a). Incremental annual costs associated with replacement formulations are estimated at approximately $1.6 million (UNEP, 2011a). These annual costs are more than offset by annual savings of nearly $4.4 million associated with lower blowing agent costs.

### IV.4.3.2 HCs in Commercial Refrigeration

This option replaces HFC-245fa used in commercial refrigeration foam with HCs, namely cyclopentane and cyclopentane/isopentane blends. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using hydrocarbons, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design. A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Use of cyclopentane and cyclo/iso blends in commercial refrigeration has a particularly good balance between foam properties and density. Such HC blends are associated with low operating costs and are well-proven (UNEP, 2010; TEAP, 2012). Flammability, however, may cause a high incremental capital cost for facilities, which may be uneconomic for small or medium-sized enterprises; otherwise, hydrocarbons have low operating costs (TEAP, 2012).

This option applies to HFC-245fa in newly manufactured PU commercial refrigeration foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at about $1.26 million per facility associated with safety modifications, installation/retrofit of high-pressure foam dispensers, installation of hydrocarbon storage systems, pumps, and premixing stations, as well as, safety audits, trials, and training (TEAP, 2012; UNEP, 2011b). Incremental annual costs associated with replacement formulations are estimated at nearly $105,000 (UNEP, 2011b). These annual costs are more than offset by annual savings of about $602,000 associated with lower blowing agent costs.

### IV.4.3.3 HC in Polyurethane Spray Foams

This option replaces HFC-245fa/$CO_2$ used in PU spray foam with HCs, specifically an 80/20 blend of cyclopentane and isopentane. HCs are inexpensive and have near-zero direct GWPs. However, it should be noted that technical issues exist with using hydrocarbons, including flammability, which may render this alternative unsafe in some spray applications (TEAP, 2012). Using HCs instead of HFC-245fa/$CO_2$ in PU spray foam would eliminate HFC emissions during application (first year) and over the product lifetime (USEPA, 2009).

This option applies to all HFC-245fa/$CO_2$ in newly manufactured PU spray foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at $15,700 per contractor for new formulations and equipment (e.g., spray nozzles), while annual operating costs are estimated at $45,200 for fire retardant, worker safety training, and cost increases from blowing agent density change. These annual costs are offset by annual savings of $50,400 associated with lower blowing agent costs.

### IV.4.3.4 CO2 in Polyurethane Spray Foams

This option replaces HFC-245fa/$CO_2$ blends used in PU spray foam with $CO_2$ (water). In the process of using $CO_2$ (water) in foams, first isocyanate and the polyol or polyamine react to form a polymer, which forms a solid. Water is introduced and a chemical reaction between the water and polymeric isocyanate produces $CO_2$, which is used as a blowing agent. Using $CO_2$ (water) instead of HFC-245fa in PU spray foams eliminates HFC emissions during the production and application stages and over the product lifetime (USEPA, 2009). $CO_2$ is considered to have moderate foam properties (due to its high thermal conductivity and high density), and requires greater thickness that leads to a cost penalty compared to other options (TEAP, 2012). The use of $CO_2$ in this application is most predominant in Japan, with reported use also in North America and Spain (UNEP, 2010).

This option applies to all HFC-245fa/$CO_2$ in newly manufactured PU spray foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. One-time costs are estimated at $4,600 per contractor (for new formulations and minimal equipment modifications), while annual operating costs are estimated at $60,700 (for fire retardant and the cost increase from blowing agent density change). These annual costs are partly offset by annual savings of $10,700 associated with lower agent costs.

### IV.4.3.5 LCD/Alcohol in XPS Boardstock

This option replaces the HFC-134a and $CO_2$-based blends used in extruded polystyrene (XPS) boardstock foam with liquid $CO_2$ (LCD)/alcohol. LCD is blended with other foam components under pressure prior to the initiation of the chemical reaction. When decompressed, the $CO_2$ expands, resulting in froth foam that further expands with the additional release of $CO_2$ from the water/isocyanate resin reaction that forms the PU foam matrix. Difficulties encountered in using LCD include the limited solubility of the chemical mixture, controlled decompression, and distribution of the unavoidable froth (USEPA, 2009). Foams blown with $CO_2$ may suffer from lower thermal performance, lower dimensional stability, and higher density versus fluorocarbon-blown foams (USEPA, 2009). To overcome these limitations, $CO_2$ can be blended with HCs or HFCs (Williams et al., 1999; Honeywell, 2000; Alliance, 2001).

This option applies to all HFC-134a/$CO_2$ blends in newly manufactured XPS boardstock foam. This option is not applied in developing countries, because no HFC consumption is assumed in this application in the baseline. This analysis assesses the costs for the foam producer to replace an HFC-134a/$CO_2$-based blend with LCD/alcohol in one of 10 production lines. One-time costs are estimated at

$5,856,000 per facility (for equipment, safety, and incineration considerations), while annual operating costs are estimated at $915,000 (for labor, energy, and lost capacity). These annual costs are offset by annual savings of $4,770,000 associated with lower costs for agent and polystyrene resin.

### IV.4.3.6 HFC-134a to HCs in PU One-Component Foam

This option replaces HFC-134a used in PU one-component foam with HCs, specifically a 50/50 blend of propane and butane. HCs are inexpensive and have near-zero direct GWPs. Technical issues exist with using HCs, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design (USEPA, 2009). A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Use of butane and propane in one component foams is well proven and is associated with low operating costs (TEAP, 2012). Using HCs instead of HFC-134a in PU one-component foams eliminates HFC emissions during manufacturing and over an assumed product lifetime of 1 year (USEPA, 2009).

This option applies to all HFC-134a in newly manufactured PU one-component foam in both developed and developing countries. One-time costs are estimated at $399,000[3] per facility (for capital costs and safety equipment), while annual operating costs are estimated at $342,000 (for fire retardant and worker safety training). These annual costs are offset by annual savings of $859,000 associated with lower agent costs.

### IV.4.3.7 HFC-152a to HCs in PU One-Component Foam

Similar to the option above, this option replaces HFC-152a used in PU one-component foam with HCs, specifically a 50/50 blend of propane and butane.

This option applies to all HFC-152a in newly manufactured PU one-component foam. This option is not applied in developing countries, because no baseline HFC-152a consumption is assumed in this application. One-time costs are estimated at $399,000 per facility (for capital costs and safety equipment), while annual operating costs are estimated at $342,000 (for fire retardant and worker safety training). These annual costs are offset by annual savings of $409,000 associated with lower agent costs.

### IV.4.3.8 HCs in PU Continuous and Discontinuous Foams

This option replaces HFC-134a used in PU continuous and discontinuous panel foam with HCs. HCs are inexpensive and have near-zero direct GWPs. Some technical issues exist with using HCs, such as flammability and lower insulation performance, but these can be overcome through proper safety controls and engineering design (USEPA, 2009). A significant advantage of hydrocarbons is that they can be easily blended to impact a range of properties, such as thermal performance, cell gas pressure, and foam density, as well as cost (TEAP, 2012). Using HCs instead of HFC-134a in PU continuous and discontinuous panel foam eliminates HFC emissions during the manufacturing stage, during the foam's assumed 50-year lifetime, and at time of product disposal (USEPA, 2009).

This option is assumed to be applicable to all HFC-134a in newly manufactured PU continuous and discontinuous panel foam. This option is not applied in developing countries, because no HFC

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[3] In developing countries, it is assumed that capital costs are 10% higher than those in the United States.

consumption is assumed in this application in the baseline. One-time costs are estimated at $319,000 per facility (for capital costs and safety equipment), while annual operating costs are estimated at $2,490,000 (for fire retardant, worker safety training, and changes in foam density). These annual costs are offset by annual savings of $2,937,000 associated with lower agent costs.

### IV.4.3.9 Manual Blowing Agent Recovery from Appliances at End of Life (EOL)

In most countries,[4] foams contained in appliances and other products typically end up in landfills, where the remaining blowing agent still contained in the insulation at the end of the product's life is released during shredding and compaction or slowly over time (CARB, 2011). This option involves manual labor to disassemble appliances and remove the foam in large pieces; the recovered foam is then sealed in plastic bags to prevent further off-gassing of the blowing agent and subsequently sent for incineration in a waste-to-energy plant. This practice is currently being used in the United States and Canada, where voluntary programs and/or demand-side management programs are in place to encourage the safe disposal of inefficient appliances (CARB, 2011).

This abatement option applies to existing domestic refrigerators reaching disposal. This option is not applied in the European Union or in developing countries, because no baseline HFC consumption is assumed in PU appliances (further, recovery of foam at appliance equipment EOL is assumed in the EU baseline). One-time costs are estimated at $1 million per facility (for automated saws), while net annual operating costs are estimated at $4,865,000 per facility for labor and handling costs (CARB, 2011).

### IV.4.3.10 Fully Automated Blowing Agent Recovery from Appliances at EOL

Similar to the previous option, this option involves the recovery of foam at the end of the appliance's life, but instead using fully automated appliance dismantling machines that separate all components, including the foam-blowing agent. The blowing agent is then reconcentrated and sent to a destruction facility approved to destroy ODS, while the remaining foam fluff is typically sent to a landfill. Fully automated appliance recycling technologies can handle an estimated annual throughput of 150,000 to 250,000 units (CARB, 2011).

This abatement option applies to existing domestic refrigerators reaching disposal. This option is not applied in the European Union or in developing countries, because no baseline HFC consumption is assumed in this application. One-time costs are estimated at $5,000,000 per facility (for the fully automated unit), while net annual operating costs are estimated at $6,130,000 per facility for labor, handling, and electricity costs (CARB, 2011).

### IV.4.3.11 Solstice Liquid Blowing Agent in PU Foams

Solstice Liquid Blowing Agent[5] produced by Honeywell (also referred to as Solstice LBA, Solstice 1233zd(E), or Trans-1-chloro-3,3,3-trifluoroprop-1-ene) is under development/in early commercialization

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[4] Foam recovery from disposed appliances is already mandatory in a number of countries, including Japan and the European Union.

[5] Other unsaturated HFCs and HCFCs with low GWPs are being developed by DuPont and Arkema, among others, for use in PU and other foam applications, which are likely to be commercialized in the coming years. Although these compounds are not yet commercialized, they may be expected to have similar GWPs and applications as the Solstice compounds described here.

to replace HFC-134a and HFC-245fa used in a range of PU foam applications, including appliance foam, commercial refrigeration foam, continuous and discontinuous panel foam, and spray foam (TEAP, 2012). The blowing agent has been approved in the United States, Japan, European Union (up to 10MT), India, and Asia Pacific, South America, Central America, Middle East, and Africa regions (Honeywell, 2012a). The first commercial manufacture is expected to occur in 2013 (TEAP, 2012). Recently, Whirlpool announced that by 2014, Solstice LBA will be used in all of the company's refrigerators produced in the United States (Whirlpool, 2012). Solstice LBA has a GWP of 4.7 to 7 (USEPA, 2012b). The foam blowing agent is also considered to be nonflammable (Honeywell, 2012a), which could limit capital costs to convert from an HFC to this product. Solstice LBA exhibits relatively high performance and is considered a drop-in alternative to HFCs, with no additional capital costs (TEAP, 2012). Any significant cost is expected to be the result of the incremental cost of the blowing agent, which is expected to range from $11/kg to $17/kg (TEAP, 2012; Williams, 2013), but which may be lower, especially once production volume increases. Recent evaluations showed up to a 4% improvement in energy efficiency compared to HFC-245fa in domestic refrigerators (TEAP, 2012; Honeywell, 2012a), and a 5% to 10% energy performance improvement compared to HFC-245fa in spray and panel foams (Honeywell, 2012a), making it an attractive and likely option for markets where thermal insulation properties of the foam are important, such as in domestic refrigerators. With its low GWP, Solstice 1233zd(E) could be used in lieu of HC abatement options analyzed above for PU foams applications and achieve similar emission reductions, but at different costs. Because it is nonflammable and of similar properties as the HFCs it would replace, it would avoid some of the barriers due to pressure and flammability that exist with the other options, such as in PU spray foam, and hence may penetrate those markets further or faster than the options currently analyzed. This option is not quantitatively assessed in this analysis but may be added as a future update.

### IV.4.3.12 Solstice Gas Blowing Agent in XPS Foam and One-Component Foam

Solstice Gas Blowing Agent[6] (also referred to as Solstice GBA, Solstice 1234ze(E), and HFO-1234ze) can replace HFC-134a used in PU one-component foam and is under development/in early commercialization to replace HFC-134a in XPS foam beginning in 2013. The blowing agent has been commercial since 2008, with initial sales starting in the EU and Japan; approval for sales in the United States was awarded in 2011 (Honeywell, 2012a). The GWP of Solstice GBA is <6 and it is considered to be nonflammable up to temperatures of 28°C (82.4°F) (TEAP, 2012). In XPS foam, Solstice GBA has shown good insulation performance (i.e., energy efficiency) and compressive strength and dimensional stability similar to HFC-134a, and allows extrusion of thick foam (Honeywell, 2012a), making it an attractive and likely option for markets where such properties of the foam are important, such as in XPS foam. Solstice GBA can be used as a near drop-in replacement for HFC-134a, and can be handled, transported, and stored in the same manner (Honeywell, 2012b). Transition to Solstice GBA is anticipated to require negligible capital costs (TEAP, 2012; Williams, 2013). Any significant cost is expected to be the result of the incremental cost associated with the blowing agent, which is estimated to range from $11/kg to $17/kg (TEAP, 2012; Williams, 2013) but which may be lower, especially once production volume increases. With its low GWP, HFO-1234ze(E) could be used in lieu of LCD/alcohol in XPS foam and hydrocarbons in one-

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[6] Other unsaturated HFCs and HCFCs with low GWPs are being developed by DuPont and Arkema, among others, in XPS, one-component, and other foam, which are likely to be commercialized in the coming years. These compounds may be expected to have similar GWPs and applications as the Solstice compounds described here.

component foam and achieve similar emission reductions, but at different costs. Because it is nonflammable and of similar properties as the HFCs it would replace, it would avoid some of the barriers due to controlling decompression and flammability that exist with the other options, and hence may penetrate those markets further or faster than the options currently analyzed. This option is not quantitatively assessed in this analysis but may be added as a future update.

### IV.4.3.13 Methyl Formate in PU and XPS Foams

Methyl formate may replace HFCs in commercial refrigeration, continuous and discontinuous panels, spray foam, transport refrigeration foam, and XPS foam. It is currently used in PU spray foams internationally, including Africa, Asia, Americas, Australia, China, and Europe (Ecomate, 2012). Methyl formate was approved as a "Generally Recognized as Safe" substance by the U.S. Food and Drug Administration (Ecomate, 2012) and has a negligible GWP (TEAP, 2012). It may be blended with polyols to produce non-flammable blends that reduce conversion costs (TEAP, 2012). In commercial refrigeration and panel foam, corrosion protection is recommended and may require moderate incremental capital costs (TEAP, 2012). This option is reportedly associated with a 10% increase in operating costs due to the need for higher densities to address foam instability (UNEP, 2010). Generally, use of this alternative does not require large capital changes to facilities (Ecomate, 2012). One producer of rigid foams for refrigerated transport applications in Brazil completed conversion to methyl formate within 3 years and has since reported an increase in the productivity of the lines and reduced operational costs compared to HFC-134a (Crestani, 2012). Relative to hydrocarbon systems, methyl formate is safer to handle, and has lower shipping, handling, and storage costs (Ecomate, 2012). The GWP of methyl formate is similar to that of the options examined in this report; hence, emission reductions would be similar. Due to a lack of readily available cost information on this alternative, this option is not quantitatively assessed in this analysis.

## IV.4.4 Engineering Cost Data Summary

Table 4-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

**Table 4-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Facility Type | Project Lifetime (Years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| **Appliance: HFCs to HCs** | PU appliance foam manufacturing facility | 25 | $4,831,000 | $4,375,000 | $1,610,000 | 509,951 |
| **Commercial refrigeration: HFCs to HCs** | PU commercial refrigeration foam manufacturing facility | 15 | $1,260,000 | $602,000 | $105,000 | 66,500 |
| **Spray: HFC245fa/CO2 to HC** | PU spray foam contractor | 25 | $15,700 | $50,400 | $45,200 | 54,654 |
| **Spray: HFC245fa/CO2 to CO2** | PU spray foam contractor | 25 | $4,600 | $10,700 | $60,700 | 54,654 |
| **XPS: HFC134a/CO2 to LCD/alcohol** | XPS boardstock production facility | 25 | $5,856,000 | $4,770,000 | $915,000 | 9,168 |
| **One-component: HFC-134a to HCs — Developed** | One-component foam manufacturing facility | 25 | $399,000 | $859,000 | $342,000 | 169,603 |

(continued)

Table 4-3: Engineering Cost Data on a Facility Basis (continued)

| Abatement Option | Facility Type | Project Lifetime (Years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| **One-component: HFC-134a to HCs—Developing** | One-component foam manufacturing facility | 25 | $438,900 | $859,000 | $342,000 | 169,603 |
| **One-component: HFC-152a to HCs** | One-component foam manufacturing facility | 25 | $399,000 | $409,000 | $342,000 | 18,265 |
| **Continuous and discontinuous: HFC134a to HCs** | PU continuous and discontinuous foams manufacturing facility | 25 | $319,000 | $2,937,000 | $2,490,000 | 588,900 |
| **Appliance EOL: Manual process** | Appliance demanufacturing facility using manual blowing agent recovery | 25 | $1,000,000 | — | $4,865,000 | 99,380 |
| **Appliance EOL: Fully automated process** | Appliance demanufacturing facility using fully automated blowing agent recovery | 25 | $5,000,000 | — | $6,130,000 | 177,716 |

## IV.4.5 Marginal Abatement Cost Analysis

### IV.4.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option and facility or operation. The model estimates the mitigation potential based on the percentage of the total ODS substitutes' baseline (that is, the HFC emissions from sectors that historically used ODSs) attributable to each representative facility/operation and the technical effectiveness for each technology in each facility.

### IV.4.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by facility in addition to process-specific estimates of technical applicability and market penetration. Market penetration is a modeled value that takes into account the market's willingness to adopt the option, the rate of uptake of the alternative into new foams, and the lifetime of the existing foam base. Because foam lifetimes can be decades, replacing the stock of foams with non-HFC blowing agents will take many years. The market penetration rate is modeled to capture such time lapses. Technical effectiveness figures do not account for indirect greenhouse gas impacts associated with changes in electricity consumption (e.g., for foam blowing processes or for end-of-life appliance processing), which are accounted for in the cost analysis.[7] Table 4-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

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[7] Indirect greenhouse gas emissions are not accounted for in the technical effectiveness calculations so that the analysis can show purely ODS substitute (i.e., HFC) emission reductions achievable. It is recognized that indirect GHG emissions can be significant, and such differences, to the extent data is available on such, are accounted for in the cost analyses.

Table 4-4: Technical Effectiveness Summary

| Facility/Abatement Option | Technical Applicability | Market Penetration Rate (2030)[a] | Reduction Efficiency | Technical Effectiveness (2030)[b] |
|---|---|---|---|---|
| **Appliance: HFCs to HCs—U.S./Other developed** | New PU appliances | 100% | 100% | 37% |
| **Commercial refrigeration: HFCs to HCs—Developed** | New PU commercial refrigeration units | 100% | 100% | 39% |
| **Spray: HFC245fa/CO2 to HC—Developed** | New spray foam applications | 30% | 100% | 9% |
| **Spray: HFC245fa/CO2 to CO2—Developed** | New spray foam applications | 70% | 100% | 22% |
| **XPS: HFC134a/CO2 to LCD/Alcohol—U.S./Other developed** | New XPS boardstock foam applications | 75% | 100% | 66% |
| **XPS: HFC134a/CO2 to LCD/Alcohol—EU** | New XPS boardstock foam applications | 75% | 100% | 55% |
| **One-component: HFC-134a to HCs—Developed & developing** | New PU one-component foam applications | 100% | 100% | 94% |
| **One-component: HFC-152a to HCs—Developed** | New PU one-component foam applications | 100% | 100% | 6% |
| **Continuous and Discontinuous: HFC134a to HCs—Developed** | New PU continuous and discontinuous foam applications | 100% | 100% | 49% |
| **Appliance EOL: Manual process—U.S./Other developed** | Domestic refrigerators reaching end of life | 50% | 85% | 29% |
| **Appliance EOL: Fully automated process—U.S./Other developed** | Domestic refrigerators reaching end of life | 20% | 95% | 12% |

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in the appendix F to this chapter.

[b] Technical effectiveness figures represent the percent of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts associated with increased electricity consumption (e.g., for foam blowing processes or for end-of-life appliance processing), which are accounted for in the cost analysis.

### IV.4.5.3 Estimating Abatement Project Costs and Benefits

Table 4-5 provides examples of the break-even prices calculated for each abatement measure. Project costs and benefits are calculated for model facilities and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate costs for each technology for applicable facilities. Additional details on the analyses can be found in Appendix F to this chapter.

The break-even prices presented in Table 4-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section IV.4.5.4.

**Table 4-5: Example Break-Even Prices for Abatement Measures in Foams Manufacturing**

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Appliance: HFCs to HCs** | 509,951 | 1.7 | −5.4 | 0.3 | −3.9 |
| **Commercial refrigeration: HFCs to HCs** | 66,500 | 4.2 | −7.5 | 0.8 | −4.2 |
| **Spray: HFC245fa/CO2 to HC** | 54,654 | 0.1 | −0.1 | 0.0 | −0.1 |
| **Spray: HFC245fa/CO2 to CO2** | 54,654 | 0.0 | 0.9 | 0.0 | 0.9 |
| **XPS: HFC134a/CO2 to LCD/Alcohol** | 9,168 | 117.3 | −420.5 | 17.0 | −320.2 |
| **One-component: HFC-134a to HCs—Developed** | 169,603 | 0.4 | −3.0 | 0.1 | −2.7 |
| **One-component: HFC-134a to HCs—Developing** | 169,603 | 0.5 | −3.0 | 0.1 | −2.6 |
| **One-component: HFC-152a to HCs** | 18,265 | 4.0 | −3.7 | 0.6 | −0.2 |
| **Continuous and discontinuous: HFC134a to HCs** | 588,900 | 0.1 | −0.8 | 0.0 | −0.7 |
| **Appliance EOL: Manual process** | 99,380 | 1.8 | 49.0 | 0.3 | 50.5 |
| **Appliance EOL: Fully automated process** | 177,716 | 5.2 | 34.5 | 0.8 | 38.9 |

### IV.4.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 13.7 and 37.0 $MtCO_2e$, respectively. There are 27.0 $MtCO_2e$ of reductions available in 2030 resulting from implementing currently available technologies that are economical at projected costs. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to manufacturers/users of foams, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 4-6, which shows abatement potential by major country and regional grouping at select break-even prices in 2030; Figure 4-4 illustrates the marginal abatement cost curves of the top five emitting countries.

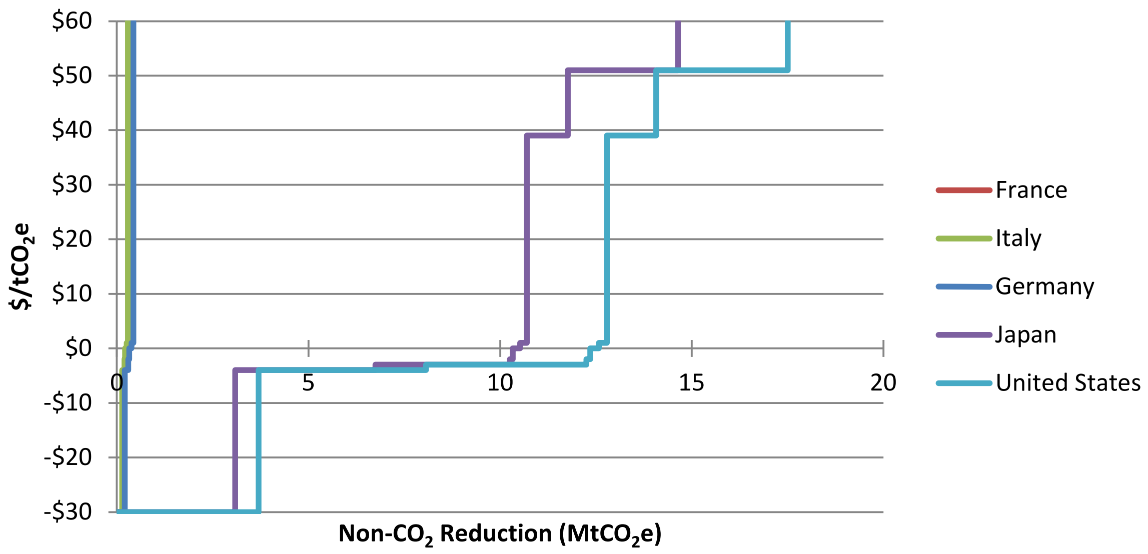
## IV.4.6 Uncertainties and Limitations

Available data on costs for abatement technologies were not scaled to reflect potential differences in the costs outside of the United States. Additional research may be required to determine actual variability in costs across regions. Moreover, the development of alternative blowing agents is quickly evolving; thus, new options may enter the market, which should be considered quantitatively in future analyses (e.g., unsaturated fluorinated compounds and methyl formate).

Table 4-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

| | Break-Even Price ($\$/tCO_{2e}$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **−10** | **−5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100 +** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| France | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Germany | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Italy | 0.1 | 0.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Japan | 3.1 | 3.1 | 10.5 | 10.7 | 10.7 | 10.7 | 10.7 | 10.7 | 11.8 | 14.6 | 14.6 |
| United States | 3.7 | 3.7 | 12.6 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 14.1 | 17.5 | 17.5 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | — | — | — | — | — | — | — | — |
| Central and South America | — | — | — | — | — | — | — | — | — | — | — |
| Middle East | — | — | — | — | — | — | — | — | — | — | — |
| Europe | 0.4 | 0.4 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 |
| Eurasia | - | - | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Asia | 0.1 | 0.1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 |
| North America | 0.3 | 0.3 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.4 | 1.4 |
| **World Total** | **8.1** | **8.1** | **27.0** | **27.7** | **27.7** | **27.7** | **27.7** | **27.7** | **30.2** | **37.0** | **37.0** |

Figure 4-4: Marginal Abatement Cost Curves for Top Five Foam Emitters in 2030



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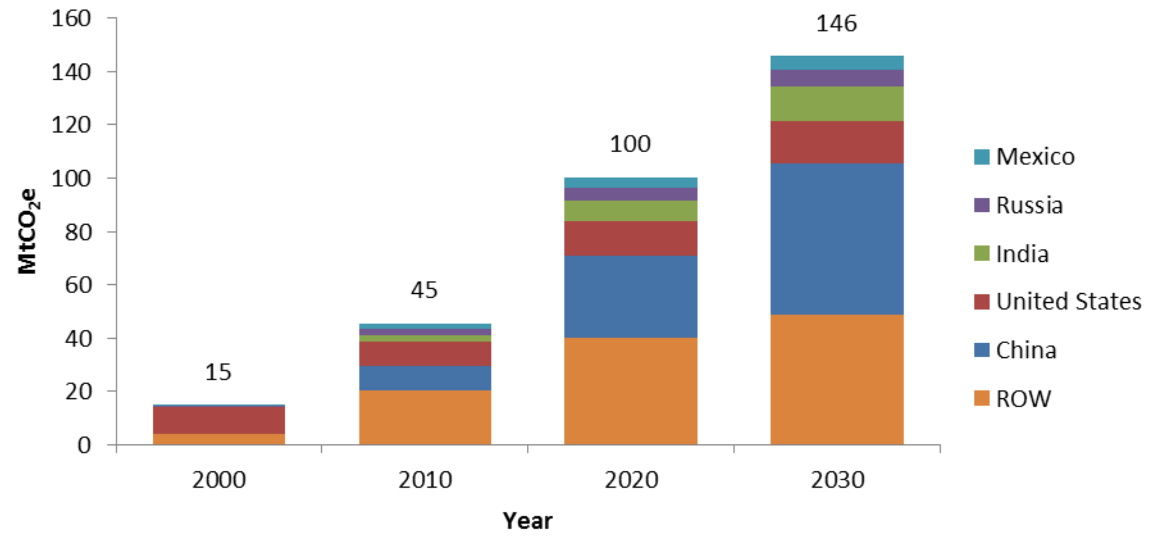
# IV.5. HFC Emissions from Aerosol Product Use

## IV.5.1 Sector Summary

Aerosol propellant formulations containing HFCs are used in a variety of consumer products, such as spray deodorants and hair sprays, and specialty aerosol uses, such as freeze spray and dust removal products. Additionally, aerosol propellants containing HFCs are used in pharmaceutical products, primarily metered dose inhalers (MDIs).

Global HFC emissions from the aerosols sector were estimated at roughly 45 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010 and are expected to climb to 146 $MtCO_2e$ by 2030 as shown in Figure 5-1. A majority of the growth is attributed to an increase in the consumption of HFCs for aerosol applications in developing countries.

**Figure 5-1: HFC Emissions from Aerosol Product Use: 2000–2030 ($MtCO_2e$)**

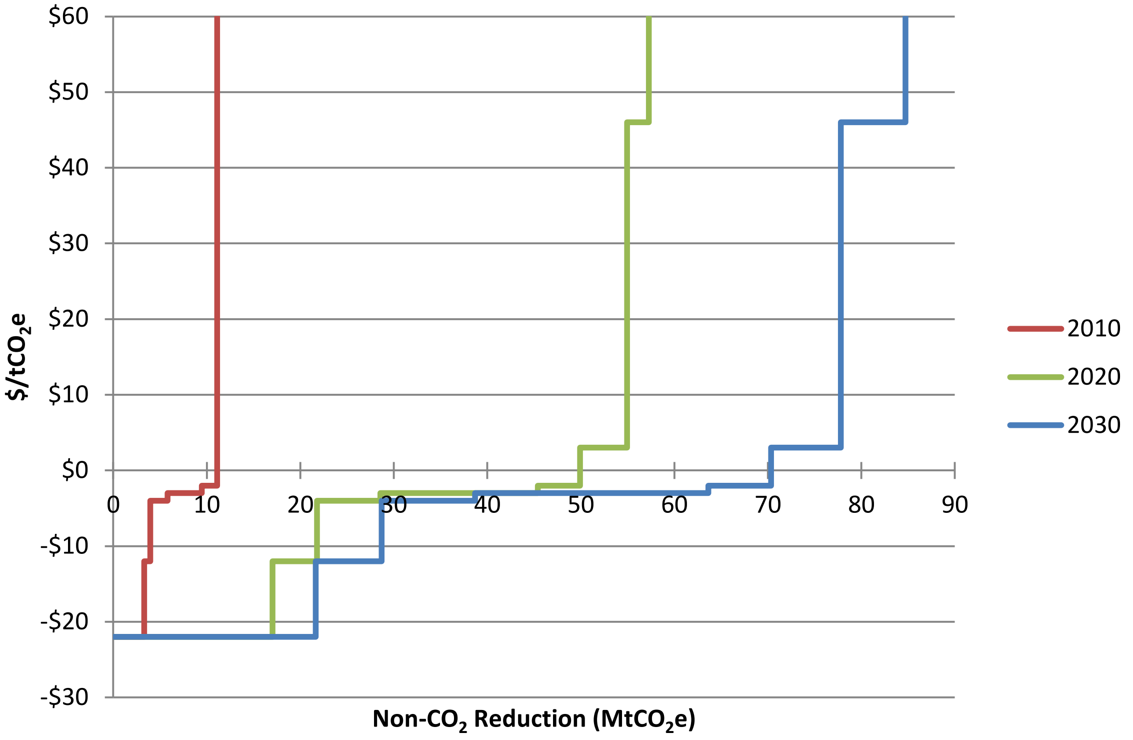


Source: USEPA, 2012.

A variety of abatement measures are available to reduce emissions. For consumer aerosol products, the options include transitioning to replacement propellants with very low global warming potentials (GWPs) and converting to a not-in-kind (NIK) alternative, such as a stick, roller, or finger/trigger pumps. Dry powder inhaler (DPI) technology is considered in this analysis as a replacement measure for MDIs.

The global abatement potential from aerosols is equal to approximately 66% of total annual emissions from the aerosols sector and 5% of total annual emissions from all sectors that use ODS substitutes. Potentially, nearly 100% abatement is possible for consumer aerosol products; whereas abatement is more limited for MDIs due to medical reasons (e.g., DPIs are not suitable for cases of severe asthma or for young children). Marginal abatement cost (MAC) curve results are presented in Figure 5-2. Maximum abatement potential in the aerosols sector is 97 $MtCO_2e$ in 2030. There are 70 $MtCO_2e$ of emissions reductions that are cost-effective at currently projected energy prices for 2030.

**Figure 5-2: Global Abatement Potential in Aerosol Product Use: 2010, 2020, and 2030**



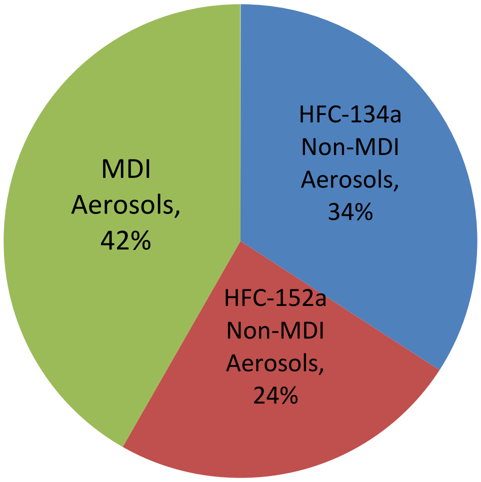
## IV.5.2 Emissions from Aerosol Product Use

Aerosol propellants are completely emitted during product use. This analysis estimates emissions from consumer aerosol products, such as spray deodorants and hair sprays, and specialty aerosol uses, such as freeze spray and dust removal products, and, separately, emissions from MDIs. HFC-134a has been introduced as an alternative propellant to chlorofluorocarbons (CFCs) in both MDIs and consumer aerosol products; in addition, HFC-227ea is used in MDIs and HFC-152a is used in consumer aerosol applications. This analysis characterizes these three categories, for the purposes of evaluating the cost of reducing HFC emissions, as follows:

- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-134a aerosol propellant charge of two ounces;
- a facility that produces 10 million consumer aerosol cans per year, with each can containing an HFC-152a aerosol propellant charge of two ounces; and
- a single 200-dose MDI aerosol unit with a charge size of 15 grams that uses HFC-134a propellant.

The relative shares of these applications are displayed in Figure 5-3.

Figure 5-3: Global HFC Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



### IV.5.2.1 Activity Data or Important Sectoral or Regional Trends

HFC emissions from the aerosols sector represented 10% of total ODS substitute emissions in 2010. Emissions were estimated based on estimated market size and charge size of aerosol products in the United States, which was then proxied to other regions based on each country's gross domestic product. Growth in aerosol products correlates with economic growth, and because of the global, commoditized nature of this sector, there are no significant regional differences in the aerosol products themselves. Aerosols are fully emissive, and the HFCs contained within the aerosol are assumed to be emitted within a year of consumption. Many non-MDI aerosols already use alternative propellants, either hydrocarbons (HCs) or manual pump mechanisms; thus, the baseline adoption of the reduction technologies is quite high in the market.

### IV.5.2.2 Emission Estimates and Related Assumptions

Global emissions of HFCs from the aerosols sector were estimated to be 45 $MtCO_2e$ in 2010, growing to 146 $MtCO_2e$ in 2030, as shown in Table 5-1. The majority of emissions are HFC-134a, with lesser amounts of HFC-152a and HFC-227ea. Emissions are projected to grow significantly as developing countries' economies grow and demand for consumer aerosols grows. Emissions were estimated using USEPA's Vintaging Model and assumptions about initial market size of the sector, the specific transitions away from CFCs in terms of timing and alternative propellant used, charge sizes, and leak rates.

## IV.5.3 Abatement Measures and Engineering Cost Analysis

A total of five abatement options were identified for the aerosols sector. For consumer aerosol products, the options are transitioning to a replacement propellant—including HCs, HFO-1234ze, and HFC-152a (for those products containing HFC-134a)—and converting to a NIK alternative, such as a stick, roller, or finger/trigger pump. Costs are analyzed by looking at a model facility that uses HFC to fill 10 million aerosol cans a year. For MDIs, the abatement measure examined by this analysis is further use of dry powder inhaler technology where suitable for the patient. Costs are analyzed based on a single DPI

Table 5-1: Projected Baseline Emissions from Aerosol Product Use: 2010-2030 ($MtCO_2e$)

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 9.4 | 23.0 | 31.2 | 42.2 | 56.9 | 9.4% |
| United States | 8.9 | 11.9 | 13.0 | 14.2 | 15.6 | 2.8% |
| India | 2.4 | 5.7 | 7.6 | 9.9 | 13.0 | 8.8% |
| Russia | 2.6 | 3.9 | 4.6 | 5.4 | 6.2 | 4.4% |
| Mexico | 1.9 | 3.7 | 4.2 | 4.8 | 5.4 | 5.3% |
| **Rest of Regions** | | | | | | |
| Africa | 3.0 | 6.3 | 7.6 | 8.9 | 10.4 | 6.3% |
| Central and South America | 1.3 | 2.6 | 3.0 | 3.5 | 4.0 | 5.7% |
| Middle East | 1.8 | 3.7 | 4.4 | 5.1 | 6.0 | 6.2% |
| Europe | 9.5 | 14.6 | 15.1 | 15.6 | 16.0 | 2.6% |
| Eurasia | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 4.4% |
| Asia | 4.0 | 7.7 | 8.7 | 9.9 | 11.2 | 5.3% |
| North America | 0.2 | 0.4 | 0.4 | 0.5 | 0.5 | 4.6% |
| **World Total** | **45.5** | **84.2** | **100.4** | **120.7** | **145.8** | **6.0%** |

[a] CAGR = Compound Annual Growth Rate

Source: U.S. Environmental Protection Agency (USEPA), 2011

compared to a single MDI, with estimated cost data that incorporates the cost associated with avoided use of HFC-134a propellant, the increase in the cost of DPI treatment, the cost to market the new treatment, and the cost to retrain the patients in using the DPI (Ecofys, 2000; Enviros, 2000). Table 5-2 summarizes the applicability of each abatement option to the aerosol emission categories. The subsequent subsections describe each abatement option in more detail.

### IV.5.3.1 Hydrocarbons

This option replaces HFC-134a or HFC-152a in non-MDI aerosols with an HC-based propellant. HC aerosol propellants are usually mixtures of propane, butane, and isobutane.[1] Their primary advantage lies in their affordability; the price of HC propellants which range from one-third to one-half that of HFCs. The main disadvantages of HC aerosol propellants are flammability concerns and, because they are volatile organic compounds (VOCs), their contribution to ground-level ozone and smog. Despite these concerns, HC aerosol propellants already hold a sizable share of the market and may be acceptable for additional applications.

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[1] For calculation purposes, a GWP of 3.48 is used based on an average of the GWP of propane (GWP=3.3) and isobutane (GWP=3.65).

**Table 5-2: Aerosol Product Use Abatement Options**

| Abatement Option | Reduction Efficiency | | | Applicability |
|---|---|---|---|---|
| | Consumer Aerosol Facility/ HFC 134a | Consumer Aerosol Facility/ HFC 152a | Metered Dose Inhaler | |
| **Consumer Aerosol Products** | | | | |
| Hydrocarbon | 99.7% | 97.5% | NA | Consumer aerosol facility/HFC-134a/HFC-152a |
| Not-in-kind | 100% | 100% | NA | Consumer aerosol facility/HFC-134a/HFC-152a |
| HFO-1234ze | 99.5% | 95.7% | NA | Consumer aerosol facility/HFC-134a/HFC-152a |
| HFC-134a to HFC-152a | 89.2% | | | Consumer aerosol facility/HFC-134a |
| **Pharmaceutical Aerosol Products (MDIs)** | | | | |
| Dry powder inhalers | NA | NA | 100% | Metered dose inhaler |

Costs of converting filling facilities to accept HC propellants can range from $10,000 to potentially as high as $1.2 million; the one-time cost varies based on the need for investments in new equipment and the need to relocate to regions where the use of HCs is considered safe (Nardini, 2002). To accommodate any flammable propellant, a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system (Techspray, 2008; MicroCare, 2008). According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008). Given that HCs (estimated at $1/lb) are lower cost than HFC-134a or HFC-152a (estimated at $3/lb and $2/lb, respectively), the adoption of this abatement measure is expected to result in an annual savings associated with gas purchases, ranging from $1 million to nearly $3 million.

### IV.5.3.2 Not-in-Kind

NIK aerosol devices include finger/trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These systems often prove to be a better and more cost-effective option than HFC-propelled aerosols, particularly in areas where a unique HFC property is not specifically needed. Because all of the HFC (either HFC-134a or HFC-152a) contained in the aerosol can is replaced with a device that does not use any GHGs, the reduction efficiency of this option is 100%.

Significant variability exists in financial components of projects targeting NIK replacements for HFC-containing aerosol products. This variability is attributable to the wide range of potential aerosol and NIK product types. A one-time cost to make the conversion is estimated at $250,000; additionally, annual costs of $500,000 are estimated to address higher material costs of the particular sticks, rollers, and pumps being used (UNEP, 1999). An annual savings is expected, ranging from $2.3 million to $4.1 million, as a result of eliminating the need for a HFC propellant.

### IV.5.3.3 HFO-1234ze

HFO-1234ze has potential application both as a propellant and also as the active ingredient in aerosol dusters. HFO-1234ze is nonflammable (at room temperature) and has physical properties that are very similar to both the HFC-134a and HFC-152a. Hence, it may be used as a 'drop-in' replacement for HFC propellants (MicroCare, 2011). The manufacturer of this chemical indicates that Europe and Japan have already begun to adopt HFO-1234ze, while interest is also rising in the United States because of awareness of environmental sustainability (Honeywell, 2011a). A number of dusters using HFO-1234ze are available today (Amazon, 2013; ITW Chemtronics, 2013; Miller Stephenson, 2013; Stanley Supply and Services, 2013). A large scale production facility is being built in the United States with an expected production of HFO-1234ze in late 2013 (Honeywell, 2011b). In the absence of regulations, adoption in Europe and Japan is expected to grow continuously at a moderate rate (reaching a maximum of 15% to 20% of today's HFC volume); therefore, this option is expected to penetrate up to 15% of the non-MDI HFC-134a market and up to 20% of the non-MDI HFC-152a market. In the United States, adoption of HFO-1234ze is expected to follow a similar path, but with a later start. In developing countries, no interest in HFO-1234ze is expected in the foreseeable future because of inexpensive options that are the preferred solutions today.

For this analysis, a one-time cost of roughly $500,000 is assumed because of the need for bulk storage. According to MicroCare (2011), although it is possible to use one ton cylinders and avoid the costs of adding bulk storage, using ton cylinders is inefficient and adds to the unit cost of the HFO material. Therefore, any facility using this material would almost certainly need to use bulk storage. This is likely a conservative (high) one-time cost estimate, considering it is about the same capital cost considered in the next section for a flammable propellant, whereas HFO-1234ze(E) is not flammable at room temperatures. Because HFO-1234ze has a higher cost than the other HFCs (i.e., HFC-134a and HFC-152a), a facility making the transition would incur a higher annual cost when adopting this propellant.

### IV.5.3.4 HFC-134a to HFC-152a

This abatement measure examines replacing HFC-134a (with a GWP of 1,300) with HFC-152a (with a GWP of 140). HFC-134a is assumed to represent 58% of non-MDI aerosols; therefore, this abatement option is only applicable to 58% of the non-MDI aerosol model facilities. HFC-134a is the primary nonflammable propellant in certain industrial products. HFC-152a possesses only moderate flammability hazards and might, therefore, be acceptable for some applications that use HFC-134a, but it may present problems for other applications.

Costs of converting filling facilities to accept HFC-152a may range from $500,000 to $600,000, (Techspray, 2008; MicroCare, 2008). To accommodate HFC-152a (or any flammable propellant), a company is required to build a storage tank to house the product. This tank will need to be connected to the main facility through a plumbing system (Techspray, 2008). Aside from the costs associated with building a storage house, no other significant expenses would be incurred. According to discussions with industry, the majority of companies would already have fire insurance and other fire safety precautions intact; therefore, no significant additional costs would be associated with housing a flammable chemical, and the increase in annual costs would be zero (Techspray, 2008; MicroCare, 2008). The lower cost of HFC-152a (compared with HFC-134a) results in an annual savings associated with gas purchases, estimated at $1.8 million for a typical aerosol filling facility.

### IV.5.3.5 Dry Powder Inhalers

Dry powder inhalers (DPIs) are a viable abatement measure for most anti-asthma drugs, although they are not successful with all patients or all drugs. Micronised dry powder, that contains the drug agent, is contained in the DPI, a non-pressurized delivery system, and is inhaled and deposited in the lungs. They are suitable only in patients who are able to inhale robustly enough to transport the powder to the lungs. DPIs are not suitable for persons with severe asthma or for young children. Unlike MDIs, powdered drug particles contained in DPIs tend to aggregate and may cause problems in areas with hot and humid climates. Other issues that doctors and patients consider when choosing a treatment device include the patient's manual dexterity, ability to adapt to a new device, and perception of the effectiveness of the medicine and taste of any added ingredients. Ultimately, these and other critical patient care issues must be assessed by the doctor and patient in choosing whether a DPI, MDI or other type of therapy is most appropriate (Price et al., 2004; UNEP, 2010). Where feasible, DPIs—which do not contain GHGs—could be used in lieu of HFC-containing MDIs; hence, the reduction efficiency of this option is 100%.

Costs incurred with using DPIs include the increased cost of DPI treatment, the cost to market the new treatment, and the cost to retrain patients to use the DPI (Enviros, 2000). The cost of research and development of new drugs and delivery mechanisms can also be significant; however, as both MDIs and DPIs are available to the market today, and due to a lack of specific cost information, such expenses are not considered in this analysis.

### IV.5.3.6 Engineering Cost Data Summary

Table 5-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price. For more detailed costs information see Appendix G.

**Table 5-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Facility/Emission Type | Project Lifetime (years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| **Consumer Aerosol Products** | | | | | | |
| HCs | Consumer aerosol/HFC-134a | 10 | $325,000 | $2,800,000 | — | 735,130 |
| | Consumer aerosol/HFC-152a | | | $1,000,000 | | 77,410 |
| Not-in-Kind | Consumer aerosol/HFC-134a | 10 | $250,000 | $4,100,000 | $500,000 | 737,100 |
| | Consumer aerosol/HFC-152a | | | $2,300,000 | | 79,380 |
| HFO-1234ze | Consumer aerosol/HFC-134a | 10 | $500,000 | — | $1,400,000 | 730,312 |
| | Consumer aerosol/HFC-152a | | | | $3,200,000 | 72,722 |
| HFC-134a to | Consumer aerosol/HFC-134a | 10 | $500,000 | $1,800,000 | — | 586,889 |
| **Pharmaceutical Aerosol Products (MDIs)** | | | | | | |
| DPIs | Metered dose inhaler | 10 | — | — | $700,000 | 1,300 |

## IV.5.4 Marginal Abatement Costs Analysis

### IV.5.4.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

### IV.5.4.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Market penetration rates vary over time as systems are upgraded in the future. Table 5-4 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of each option.

**Table 5-4: Technical Effectiveness Summary**

| Abatement Option | Technical Applicability | Market Penetration Rate (2030) | Reduction Efficiency | Technical Effectiveness (2030) |
|---|---|---|---|---|
| **Consumer Aerosol Products** | | | | |
| HFC-134a to HC | 58% | 50% | 99.7% | 29.0% |
| HFC-134a to NIK | 58% | 20% | 100.0% | 11.6% |
| HFC-134a to HFO-1234ze | 58% | 15% | 99.5% | 8.7% |
| HFC-134a to HFC-152a | 58% | 15% | 89.2% | 7.8% |
| HFC-152a to HC | 42% | 20% | 97.5% | 8.2% |
| HFC-152a to NIK | 42% | 60% | 100.0% | 25.1% |
| HFC-152a to HFO-1234ze | 42% | 20% | 95.7% | 8.0% |
| **Pharmaceutical Aerosol Products (MDIs)** | | | | |
| DPI | 100% | 20% | 100.0% | 20.0% |

[a] Technical effectiveness (TE) is the product of TA*MP*RE.

## IV.5.4.3 Estimating Abatement Project Costs and Benefits

Table 5-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities and are used in the calculation that solves for the break-even price that sets each project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for different facilities.

The break-even prices presented in Table 5-5 represent model facilities. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section 5.4.4.

**Table 5-5: Example Break-Even Prices for Abatement Measures in Aerosol Product Use**

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Consumer Aerosol Products** | | | | | |
| HFC-134a to HC | 735,130 | 0.1 | −3.8 | 0.0 | −3.7 |
| HFC-134a to NIK | 737,100 | 0.1 | −4.9 | 0.0 | −4.8 |
| HFC-134a to HFO-1234ze | 730,312 | 0.2 | 1.9 | 0.0 | 2.1 |
| HFC-134a to HFC-152a | 586,889 | 0.2 | −3.1 | 0.1 | −2.9 |
| HFC-152a to HC | 77,410 | 1.1 | −12.9 | 0.3 | −12.1 |
| HFC-152a to NIK | 79,380 | 0.9 | −22.7 | 0.2 | −22.0 |
| HFC-152a to HFO-1234ze | 72,722 | 1.9 | 44.0 | 0.5 | 45.4 |
| **Pharmaceutical Aerosol Products (MDIs)** | | | | | |
| DPI | 1,300 | 0.0 | 538.5 | 0.0 | 538.5 |

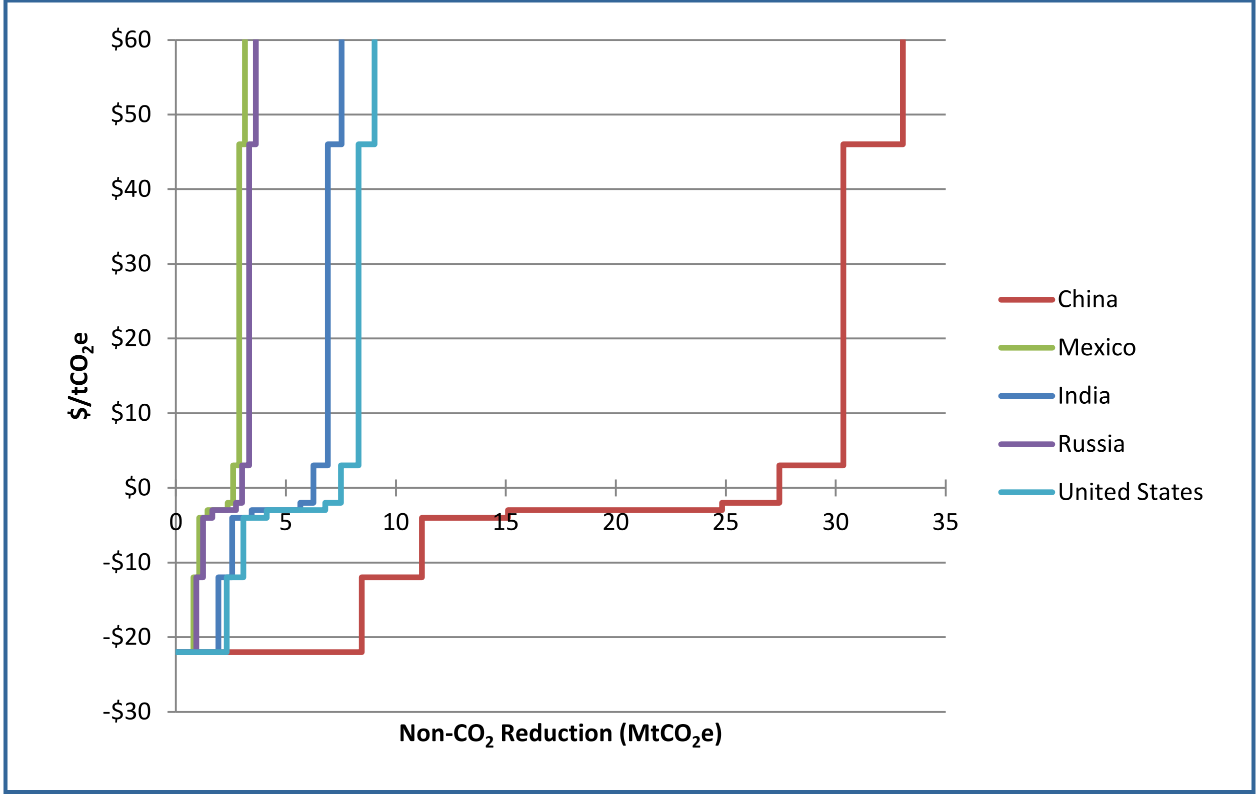
### IV.5.4.4 MAC Analysis Results

Global abatement potentials in 2020 and 2030 are 66 and 97 $MtCO_2e$, respectively. There are 70 $MtCO_2e$ of reductions in projected baseline emissions in 2030 resulting from implementing currently available technologies that are cost-effective at projected prices. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to producers of aerosols, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 5-6 and Figure 5-4 by major country and regional grouping at select break-even prices in 2030.

**Table 5-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break Even Price ($/$tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **−10** | **−5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | 11.2 | 11.2 | 27.4 | 30.4 | 30.4 | 30.4 | 30.4 | 30.4 | 33.0 | 33.0 | 37.7 |
| India | 2.5 | 2.5 | 6.2 | 6.9 | 6.9 | 6.9 | 6.9 | 6.9 | 7.5 | 7.5 | 8.6 |
| Mexico | 1.1 | 1.1 | 2.6 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 3.1 | 3.1 | 3.6 |
| Russia | 1.2 | 1.2 | 3.0 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.6 | 3.6 | 4.1 |
| United States | 3.1 | 3.1 | 7.5 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 9.0 | 9.0 | 10.3 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | 2.0 | 2.0 | 5.0 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 6.0 | 6.0 | 6.9 |
| Central and South America | 0.8 | 0.8 | 1.9 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.3 | 2.3 | 2.6 |
| Middle East | 1.2 | 1.2 | 2.9 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.5 | 3.5 | 4.0 |
| Europe | 3.1 | 3.1 | 7.7 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 9.3 | 9.3 | 10.6 |
| Eurasia | 0.2 | 0.2 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 |
| Asia | 2.2 | 2.2 | 5.4 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.5 | 6.5 | 7.4 |
| North America | 0.1 | 0.1 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| **Total** | **28.7** | **28.7** | **70.3** | **77.8** | **77.8** | **77.8** | **77.8** | **77.8** | **84.7** | **84.7** | **96.7** |

Figure 5-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



## IV.5.5 Uncertainties and Limitations

The significant areas of uncertainty in this analysis are in how costs for these mitigation technologies may vary internationally. The analysis is currently limited in the lack of detail on cost assumptions, which may not accurately represent the transition costs regionally. Additionally, the cost assumptions for the transition to DPIs are based on a study released in 2000, which may not reflect the latest technical and economic parameters. Finally, the general methodology used here projects increasing use of HFC aerosols based on historical growth and expanding GDPs. Some market sectors may not expand that quickly; for instance, HFC growth in MDIs is projected to grow from current use of 4,000 metric tons globally to 7,000-10,500 metric tons in 2015 (UNEP, 2010).

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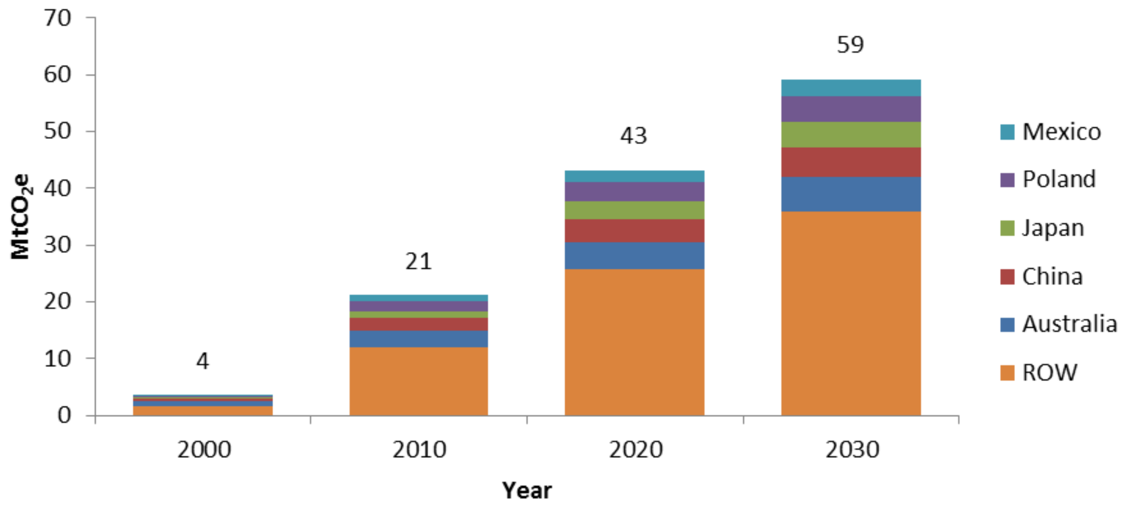
# IV.6. HFC and PFC Emissions from Fire Protection

## IV.6.1 Sector Summary

The fire protection sector emits hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) from the use of total flooding fire protection systems in fire suppression. This sector also includes portable (hand-held) fire extinguishers. Greenhouse gas emissions from the fire protection sector (excluding halons and hydrochlorofluorocarbons) were estimated at roughly 21 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010, as shown in Figure 6-1. By 2030, emissions from this sector are expected to reach over 59 $MtCO_2e$. A majority of the growth will result from increased use of HFCs in developing countries.

**Figure 6-1: HFC and PFC Emissions from Fire Protection: 2000–2030 ($MtCO_2e$)**

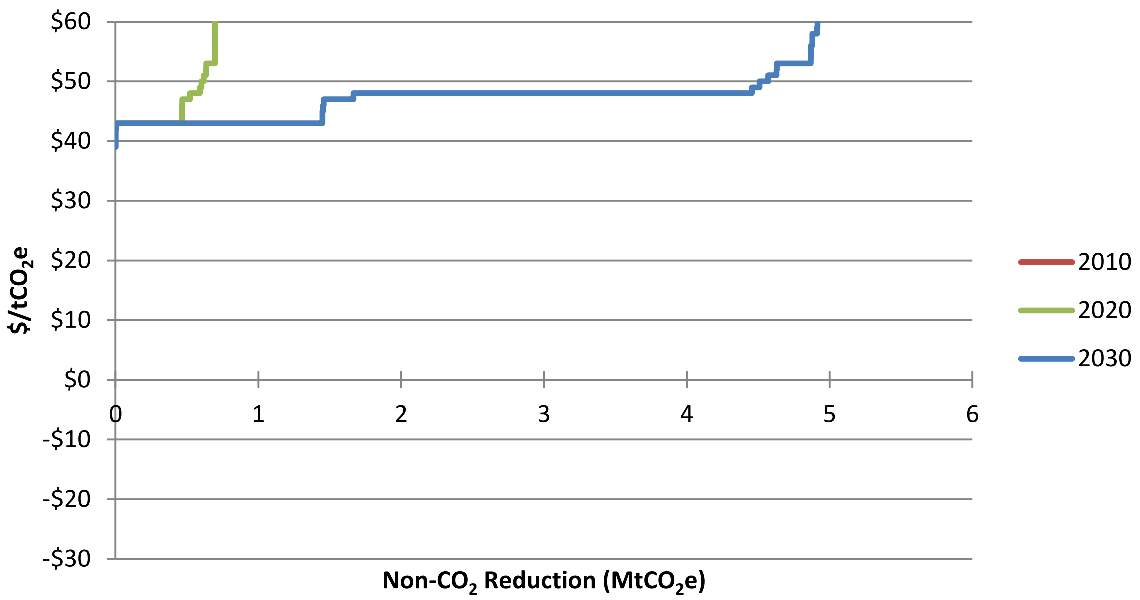


Source: USEPA, 2012.

This analysis reviews options to reduce emissions from the fire protection sector by using extinguishing agents with low global warming potential (GWP) in lieu of HFCs/PFCs in new total flooding equipment, specifically, replacement of the HFC with inert gas, water mist, or the agent FK-5-1-12.

The global abatement potential from the fire protection options reviewed is equal to approximately 11% of total annual emissions from the fire protection sector and 0.3% of total annual emissions from all sectors that use ODS substitutes. The options identified to abate emissions in the fire protection sector completely replace the fluorinated fire protection agents, however, they are assumed to only be implemented when new systems are built. Thus, their effectiveness at reducing emissions will increase over time as new systems are built, but it will take many years before the existing stock would be replaced. Marginal abatement cost (MAC) curve results are presented in Figure 6-2. Maximum abatement potential in the fire extinguishing sector is 6.4 $MtCO_2e$ in 2030. There are no emission reductions that are cost-effective at prices estimated in this analysis. No reductions are available in 2010 as a result of the assumption that the available technologies are only used for new installations and did not start to penetrate the market until 2011.

**Figure 6-2: Global Abatement Potential in Fire Protection: 2010, 2020, and 2030**



## IV.6.2 Emissions from Fire Protection

Emissions from fire protection equipment occur from equipment leakage, accidental discharges, and use during fire extinguishing. In general, fire protection systems have very low leak rates, except when discharged during a fire event. The majority of emissions associated with fire extinguishing come from the equipment's use in the total flooding market (see Figure 6-3). Portable extinguishers—used most frequently in offices, manufacturing and retail facilities, aerospace/marine applications, and homes—also use HFCs, but such use has been limited (Wickham, 2003).

For the purpose of this analysis, we considered the sector's two types of fire protection systems—(1) portable fire extinguishers (i.e., streaming applications) and (2) total flooding applications. Typical portable extinguishers contain 1.3 kg of HFC-236fa, which is assumed to be extinguished with a frequency such that emissions are 3.5%/year. The typical flooding application uses HFC-227ea; because discharge is infrequent, emissions are 2% per year.

For modeling purposes, data typical for facilities in the United States are used. Certain cost assumptions, such as capital and electricity costs, are adjusted for developing countries.[1] Otherwise, it is assumed that the costs and reductions achieved in the modeled facilities could be scaled and would be representative of the costs and reductions in other regions.

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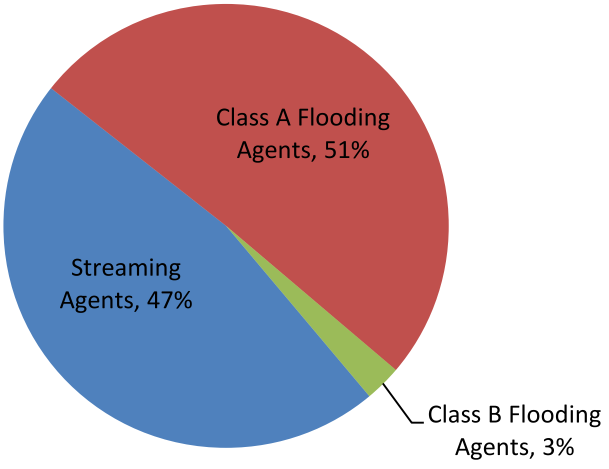
[1] In developing countries, it is assumed that capital costs are 10% higher and electricity costs are two-thirds higher relative to those in the United States.

**Figure 6-3: Global HFC and PFC Emissions in 2020 (% of GWP-Weighted Emissions)**



### IV.6.2.1 Activity Data or Important Sectoral or Regional Trends

The key activity data for fire extinguishing emissions is the consumption of the fire extinguishing agent. Fire extinguishing agent consumption is assumed to occur in all countries and to scale with a country's gross domestic product (GDP); in addition, because there are no regional differences in emission rates, emissions also scale with GDP.

Globally, HFC and PFC emissions from fire protection have been growing because of the phaseout of halon under the Montreal Protocol. Because developed countries phased out the use of halon earlier than developing countries, the growth in global emissions for the past decade has been driven by emissions from developed countries. However, because of the high GDP growth in developing countries, it is anticipated that emissions will grow more quickly from developing countries in the future.

In total flooding applications that require "clean agents,"[2] most developed countries have primarily adopted HFCs as a replacement for Halon 1301, which is being phased out under the Montreal Protocol. In developing countries, the adoption of HFCs in this application has been delayed by the slower phaseout of halon but will increase over time.

### IV.6.2.2 Emission Estimates and Related Assumptions

Global emissions from fire protection are currently estimated to be 21 $MtCO_2e$ and are projected to grow to 43 $MtCO_2e$ in 2020. Growth in emissions is driven by GDP. The emissions assume a constant

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[2] "Clean agents" are gaseous extinguishing agents that are electrically nonconductive and leave no residue.

annual release rate of 3.5% and 2% of consumption for streaming and flooding, respectively.[3] Consumption was modeled using USEPA's Vintaging Model. Emissions for major countries and regions are presented in Table 6-1.

**Table 6-1: Projected Baseline Emissions from Fire Protection: 2010 to 2030 ($MtCO_2e$)**

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| Australia | 2.9 | 4.0 | 4.8 | 5.4 | 6.0 | 3.8% |
| China | 2.2 | 3.2 | 4.0 | 4.6 | 5.2 | 4.3% |
| Japan | 1.3 | 2.2 | 3.1 | 4.0 | 4.7 | 6.7% |
| Poland | 1.7 | 2.5 | 3.3 | 4.0 | 4.5 | 5.0% |
| Mexico | 1.1 | 1.7 | 2.2 | 2.6 | 3.0 | 5.1% |
| **Rest of Region** | | | | | | |
| Africa | 1.3 | 1.9 | 2.4 | 2.7 | 3.0 | 4.5% |
| Latin America | 1.6 | 2.5 | 3.3 | 3.9 | 4.5 | 5.1% |
| Middle East | 1.8 | 2.6 | 3.3 | 3.8 | 4.3 | 4.5% |
| Europe | 3.9 | 6.6 | 9.8 | 12.4 | 13.9 | 6.6% |
| Eurasia | 0.8 | 1.5 | 2.4 | 3.2 | 3.8 | 8.5% |
| Asia | 1.8 | 2.6 | 3.2 | 3.6 | 4.1 | 4.2% |
| North America | 0.9 | 1.2 | 1.6 | 2.0 | 2.3 | 4.9% |
| **World Total** | **21.2** | **32.5** | **43.2** | **52.2** | **59.3** | **5.3%** |

[a] CAGR = Compound Annual Growth Rate
Source: U.S. Environmental Protection Agency (USEPA), 2012.

## IV.6.3 Abatement Measures and Engineering Cost Analysis

The alternatives to HFCs/PFCs in total flooding applications can be categorized as in-kind gaseous agent alternatives (i.e., $CO_2$, inert gases, fluorinated ketones) and "not-in-kind" alternatives (i.e., dispersed and condensed aerosol extinguishing systems, water sprinklers, water mist, foam, or inert gas generators). Already, climate-friendly clean agents and new not-in-kind alternative technologies have been introduced to the market.

This analysis reviews options to reduce emissions from the fire protection sector by using zero-GWP or low-GWP extinguishing agents in lieu of HFCs/PFCs in new total flooding equipment. Specifically, this analysis assesses alternative agents used in newly built total flooding systems to protect against Class A

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[3] In general, fire protection systems would be expected to have very low leak rates, except when discharged during a fire event. For modeling purposes, however, total flooding systems are assumed to have an average annual leak rate of 2% (see Appendix H to this chapter).

surface fire hazards[4] and newly built total flooding systems to protect against Class B fuel hazards[5] in large ($\geq$ 3,000 $m^3$) marine applications. All costs are presented in 2010 dollars based on the Consumer Price Index (U.S. Department of Labor, 2011).

Facilities/emissions for which no abatement options are considered in this analysis include existing total flooding systems (used to protect against all fire hazards) and all new and existing portable extinguishers. Existing flooding systems were not assessed because alternative fire protection agents require larger space requirements, rendering system retrofit costs highly dependent on the particular facility and possibly cost-prohibitive. Portable extinguishers were not assessed because emissions from this source are small, and climate-friendly alternatives are already assumed to be used widely in the baseline.

The analyzed facilities are assessed on a per-cubic meter of protected space basis, assuming an average emission rate of 2% per year. Specifically, for Class A surface fire hazards, an average of 0.633 kg of HFC-227ea is needed to protect each cubic meter of protected space; while 0.630 kg is required for large Class B fire hazards (Wickham, 2003).

Three abatement options were considered for this analysis: in new Class A total flooding systems, replacement with either FK-5-1-12 or inert gas, and in new Class B total flooding systems, replacement with water mist. Each of these options is described below in Table 6-2.

**Table 6-2: Fire Protection Abatement Options**

| Abatement Option | Applicable System Types | Reduction Efficiency |
|---|---|---|
| **FK-5-1-12** | New Class A total flooding | 100% |
| **Inert gas** | New Class A total flooding | 100% |
| **Water mist** | New Class B total flooding | 100% |

### IV.6.3.1 FK-5-1-12 in New Class A Total Flooding Applications

FK-5-1-12-mmy2 (also known as 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, and commonly referred to as FK-5-1-12) is a fluorinated ketone with an atmospheric lifetime of five days and a 100-year GWP of approximately one (Kidde Fire Protection, 2011). This option examines use of FK-5-1-12 in total flooding systems. The option is applicable in new Class A total flooding applications, replacing HFCs (primarily HFC-227ea). Class A total flooding application end-uses represent an estimated 95% of

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[4] This analysis assumes that Class A fire hazards represent an estimated 95% of the total flooding sector. This estimate is based on Wickham (2002), who estimates that over 90% of the Halon 1301 systems ever installed in the United States were designed to protect against hazards where the anticipated fire type was primarily Class A in nature and approximately 10% of the U.S. applications served by Halon 1301 had hazardous materials of the Class B type. However, because much of the former Halon 1301 Class B applications have been replaced by non-HFC alternatives (e.g., carbon dioxide), this analysis assumes that only 5% of HFC emissions from the total flooding sector are from Class B applications and the remaining 95% are from Class A applications.

[5] This analysis assumes that Class B fire hazards represent an estimated 5% of the total flooding sector, based on Wickham (2002) (as explained in previous footnote).

the total flooding sector; [6] the additional adoption of FK-5-1-12 is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are estimated at $9.49 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs are estimated at $0.03 per cubic meter of protected space for additional electricity needed to heat/cool the additional space as well as the higher agent replacement costs.

### IV.6.3.2 Inert Gas Systems in New Class A Total Flooding Applications

Inert gas systems extinguish fires using argon, nitrogen, or a blend of the two, sometimes incorporating $CO_2$ as a third component (UNEP, 2001). Inert gas systems provide an equivalent level of both fire protection and life safety/health protection in most Class A (ordinary combustible) fire hazards, including electronics and telecommunications applications. Limitations of the inert gas systems include a slower discharge time than that of HFC systems—60 seconds or more compared with 10 to 15 seconds (Kucnerowicz-Polak, 2002)—and a larger volume of agent needed than in HFC systems to extinguish fires. The weight-support structures and space needed for additional steel cylinders of gas may prohibit the retrofit of many existing HFC systems, such as those on small ships and in other applications where the system infrastructure is fixed.

This technology option is assumed to be applicable in new Class A application end uses, replacing HFCs (primarily HFC-227ea). Class A total flooding application end uses represent an estimated 95% of the total flooding sector;[7] the additional adoption of inert gas systems is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are $11.16 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs in developed countries are estimated at $0.17/cubic meter of protected space for additional electricity needed to heat/cool the additional space; the electricity costs are assumed to be two-thirds greater in developing countries. Annual costs are offset by annual savings associated with lower agent replacement costs, estimated at $0.28/cubic meter of protected space.

### IV.6.3.3 Water Mist Systems in New Class B Total Flooding Applications

Water mist systems use relatively small droplet sprays under low, medium, or high pressure to extinguish fires. These systems use specially designed nozzles to produce much smaller droplets than are produced by traditional water-spray systems or conventional sprinklers, so they use less water to extinguish a fire (UNEP, 2001; Wickham, 2002). However, some barriers have impeded broad use of water mist systems. First, these systems may be cost prohibitive in small spaces and have not proven

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[6] See footnote 4.

[7] See footnote 4.

effective in extinguishing small fires in large volume spaces (≥ 3,000 $m^3$) (IMO, 2001; Wickham, 2002). Additionally, because there is a nonlinear relationship between the volume of space and the amount of water mist needed to extinguish a given fire and because this relationship (referred to as the "mechanism of extinguishment") is not well understood, applications of water mist systems have been limited to those where fire test protocols have been developed, based on empirically tested system performance. Other market barriers for this option include additional space requirements for system storage compared with conventional HFC-227ea systems. Water mist systems can provide equivalent fire protection and life safety/health protection for Class B fuel hazards, where low temperature freezing is not a concern (USEPA, 2004).

This technology option is assumed to be applicable in large (≥3,000 $m^3$), new Class B total flooding application end uses, replacing HFCs (primarily HFC-227ea). This analysis assumes that systems designed to protect against Class B fire hazards represent an estimated 5% of the total flooding sector;[8] the additional adoption of water mist systems is assumed to only occur when new systems are installed because replacing installed systems may be cost prohibitive.

For cost modeling purposes, this option is assumed to replace the use of HFC-227ea. One-time costs are estimated at $13.14 per cubic meter of protected space in developed countries; these costs are associated with installation and equipment, as well as construction of additional floor space needed to house large volumes of extinguishing agent. In developing countries, these capital costs are assumed to be 10% higher to account for higher tariffs. Annual costs in developed countries are estimated at $0.36/cubic meter of protected space for additional electricity needed to heat/cool the additional space; these electricity costs are assumed to be 81% greater in developing countries. Annual costs are partly offset by annual savings associated with lower agent replacement costs, estimated at $0.28/cubic meter of protected space.

## IV.6.4 Engineering Cost Data Summary

Table 6-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

## IV.6.5 Marginal Abatement Cost Analysis

This section describes the methodological approach to the international assessment of abatement measures for fire extinguishing.

### IV.6.5.1 Methodological Approach

The analysis is based on the above representative project costs for model facilities in the developing and developed world. We applied the costs to calculate the break-even prices for each appropriate option for each country. The model estimates the mitigation potential based on the percentage of the total ODS substitutes baseline attributable to each representative facility and the technical effectiveness for each technology in each facility.

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[8] See footnote 3.

**Table 6-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Facility Type | Project Lifetime (years) | Capital Cost (2010 USD) | | Annual Revenue (2010 USD) | Annual O&M Costs, (2010 USD) | | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|---|---|
| | | | Developed | Developing | | Developed | Developing | |
| **FK-5-1-12** | New Class A total flooding | 20 | $9.49 | $10.44 | — | $0.03 | $0.03 | 0.04 |
| **Inert gas** | New Class A total flooding | 20 | $11.16 | $12.28 | $0.28 | $0.17 | $0.31 | 0.04 |
| **Water mist** | Large, New Class B total flooding | 20 | $13.14 | $14.45 | $0.28 | $0.36 | $0.65 | 0.04 |

## IV.6.5.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/class/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by Class (A or B), in addition to process-specific estimates of technical applicability and market penetration. Market penetration rates vary over time; the market penetration used in this calculation is a modeled value that represents the assumed rate of penetration of the abatement option into fire protection systems over time, market willingness to adopt the option, and the turnover rate of existing fire protection systems. Table 6-4 summarizes these assumptions and presents technical effectiveness parameters used in the MAC model.

**Table 6-4: Technical Effectiveness Summary**

| Facility Abatement Option | Technical Applicability | Market Penetration Rate (2030)[a] | Reduction Efficiency | Technical Effectiveness (2030)[b] |
|---|---|---|---|---|
| **FK-5-1-12—Developed** | New Class A total flooding | 40% | 100% | **31%** |
| **FK-5-1-12—Developing** | New Class A total flooding | 40% | 100% | **12%** |
| **Inert gas systems—Developed** | New Class A total flooding | 30% | 100% | **20%** |
| **Inert gas systems—Developing** | New Class A total flooding | 20% | 100% | **6%** |
| **Water mist systems—Developed** | New Class B total flooding | 75% | 100% | **3%** |
| **Water mist systems—Developing** | New Class B total flooding | 50% | 100% | **1%** |

[a] Market penetration assumptions for this analysis vary over time, and the technical effectiveness values are based on the cumulative market penetration rates assumed until that point. More information on the market penetration assumptions is provided in Appendix H to this chapter.

[b] Technical effectiveness figures represent the percentage of baseline emissions from the relevant facility type that can be abated in 2030; figures do not account for indirect greenhouse gas impacts associated with increased electricity consumption for heating/cooling of additional space, which is accounted for in the cost analysis.

### IV.6.5.3 Estimating Abatement Project Costs and Benefits

Table 6-5 provides an example of how the break-even prices are calculated for each abatement measure. Project costs and benefits are calculated for model facilities in developed and developing countries and are used in the calculation that solves for the break-even price that sets the project's benefits equal to its costs. The previous section describes the assumptions used to estimate different costs for developed and developing countries. All options have positive break-even costs, because the costs of building and maintaining additional space are not offset by any available savings associated with lower agent replacement costs.

**Table 6-5: Example Break-Even Prices for Abatement Measures in Fire Protection**

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($/$tCO_2e$) | Net Annual Cost ($/$tCO_2e$) | Tax Benefit of Depreciation ($/$tCO_2e$) | Break Even Price[a] ($/$tCO_2e$) |
|---|---|---|---|---|---|
| **Developed** | | | | | |
| FK-5-1-12 | 0.04 | 50.6 | 0.8 | 8.6 | 42.8 |
| Inert gas systems | 0.04 | 59.6 | -2.8 | 10.1 | 46.6 |
| Water mist systems | 0.04 | 70.4 | 2.2 | 12.0 | 60.6 |
| **Developing** | | | | | |
| FK-5-1-12 | 0.04 | 55.7 | 0.8 | 9.5 | 47.1 |
| Inert gas systems | 0.04 | 65.5 | 1.0 | 11.2 | 55.4 |
| Water Mist Systems | 0.04 | 77.4 | 10.2 | 13.2 | 74.4 |

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

The break-even prices presented in Table 6-5 represent model facilities for developed and developing countries. Actual prices vary by country because of the scaling of costs and benefits by international price factors. Complete international MAC results are presented in Section IV.6.5.4.

### IV.6.5.4 MAC Analysis Results

Global abatement potential in 2020 and 2030 is 0.7 and 6.4 $MtCO_2e$, respectively. There are no reductions in projected baseline emissions resulting from implementing currently available technologies that are cost-effective at projected prices. If an additional emissions reduction value (e.g., tax incentive, subsidy, or tradable emissions reduction credit) above the zero break-even price were available to users or installers of fire extinguishing systems, then additional emission reductions could be cost-effective. The results of the MAC analysis are presented in Table 6-6 and Figure 6-4 by major country and regional grouping at select break-even prices in 2030.

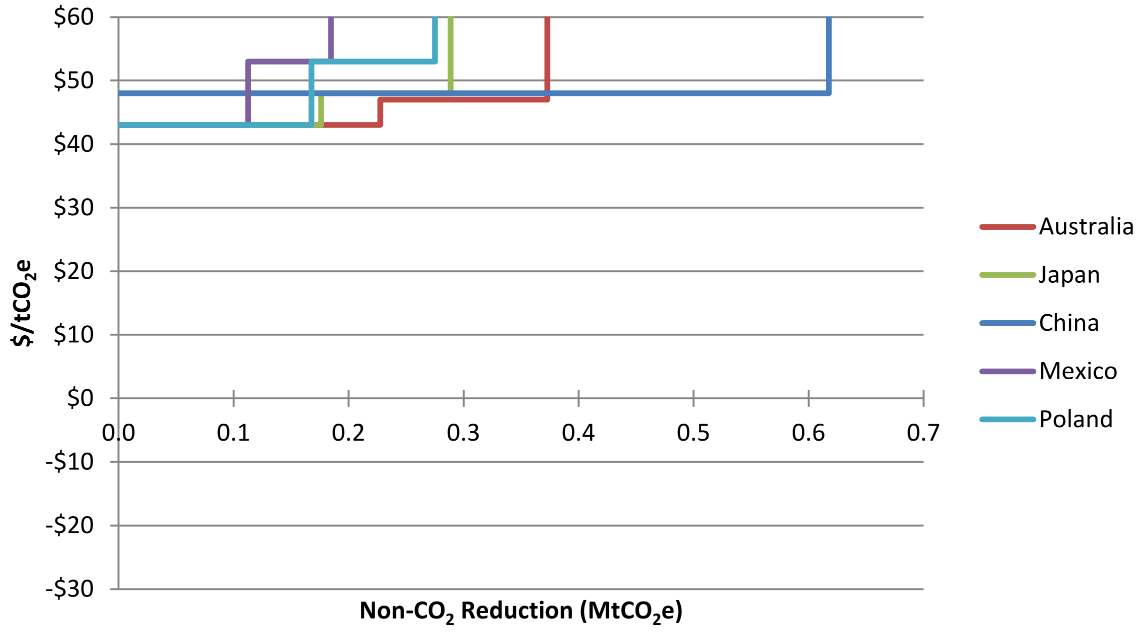
## IV.6.6 Uncertainties and Limitations

One area of uncertainty is how capital costs for these mitigation technologies may vary internationally; cost estimates were developed for several countries when possible. In addition, it should be noted that the global implementation of each option is based on information currently available and expert opinion. Great uncertainty is associated with future projections of market behavior.

Table 6-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

| | Break-Even Price ($\$/tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **–10** | **–5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| Australia | — | — | — | — | — | — | — | — | 0.4 | 0.4 | 0.4 |
| China | — | — | — | — | — | — | — | — | 0.6 | 1.0 | 1.0 |
| Japan | — | — | — | — | — | — | — | — | 0.3 | 0.3 | 0.3 |
| Mexico | — | — | — | — | — | — | — | — | 0.1 | 0.2 | 0.2 |
| Poland | — | — | — | — | — | — | — | — | 0.2 | 0.3 | 0.3 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | — | — | — | — | — | 0.4 | 0.6 | 0.6 |
| Central and South America | — | — | — | — | — | — | — | — | 0.5 | 0.7 | 0.7 |
| Middle East | — | — | — | — | — | — | — | — | 0.4 | 0.7 | 0.7 |
| Europe | — | — | — | — | — | — | — | — | 0.8 | 0.9 | 0.9 |
| Eurasia | — | — | — | — | — | — | — | — | 0.5 | 0.7 | 0.7 |
| Asia | — | — | — | — | — | — | — | — | 0.3 | 0.5 | 0.5 |
| North America | — | — | — | — | — | — | — | — | 0.1 | 0.1 | 0.1 |
| **Total** | **—** | **—** | **—** | **—** | **—** | **—** | **—** | **—** | **4.6** | **6.4** | **6.4** |

Figure 6-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030



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# IV.7. PFC Emissions from Primary Aluminum Production

## IV.7.1 Sector Summary

Emissions of the perfluorocarbons (PFCs)—perfluoromethane ($CF_4$) and perfluoroethane ($C_2F_6$)—are generated during brief process upset conditions in the aluminum smelting process. During the aluminum smelting process, when the alumina ($Al_2O_3$) in the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur. These voltage excursions are termed "anode effects" (AEs). AEs produce $CF_4$ and $C_2F_6$ emissions when carbon from the anode, instead of reacting with alumina, as it does during normal operating conditions, combines with fluorine from the dissociated molten cryolite bath. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these AEs; the more frequent and long-lasting the AEs, the greater the emissions.[1]

Global emissions of PFCs from primary aluminum production declined from 2000 to 2010, which is likely due to a variety of factors including improvement in process performance of existing smelter capacity, closure of high emitting facilities, and addition of low emitting new smelting capacity. However, global emissions of PFCs from this sector are expected to increase from an estimated value of 26 million metric tons of carbon dioxide equivalent ($MtCO_2e$) in 2010 to a projected value of 37 $MtCO_2e$ in 2030 (USEPA, 2012) (see Figure 2-1).[2] This projected increase is largely the result of an anticipated increase in demand for primary aluminum globally over the same period that is increasing at a higher rate than the assumed decrease in PFC emissions intensities (see Emissions from Aluminum Production below).

Five different electrolytic cell types are used to produce aluminum: Vertical Stud Soderberg (VSS), Horizontal Stud Soderberg (HSS), Side-Worked Prebake (SWPB), Center-Worked Prebake (CWPB), and Point Feed Prebake (PFPB).[3] PFPB is considered the most technologically advanced process to produce aluminum and all new greenfield smelters built in the world today utilize this technology. Existing, older and higher PFC emitting PFPB systems can further improve their anode effect performance by implementing management and work practices, as well as improved control software. Facilities using VSS, HSS, SWPB, and CWPB cells can reduce emissions by retrofitting smelters with emission-reducing technologies such as computer control systems and point-feeding systems, by shifting production to PFPB technology, and by adopting management and work practices aimed at reducing PFC emissions.

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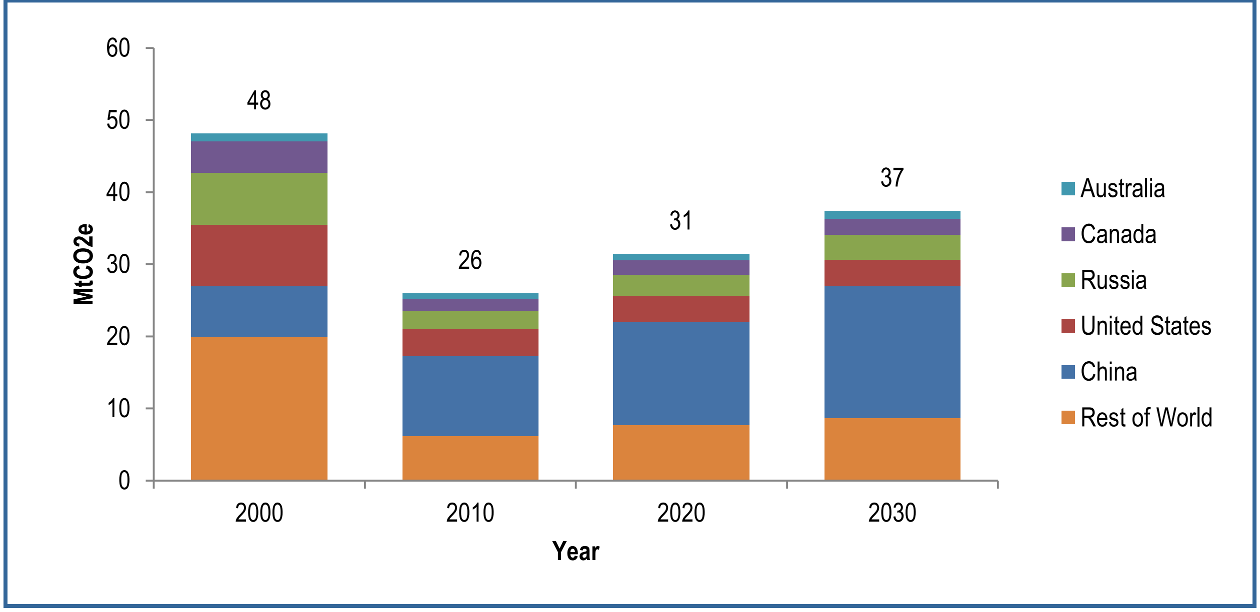
[1] It should be noted that over the last several years there has been the discovery and documentation of non-anode effect (NAE) related emissions. USEPA has supported some of the most significant work on NAE emissions. These emissions can be a significant, perhaps the major, source of PFC emissions in some smelter cells. It should also be noted that NAE emissions and NAE abatement measures are not addressed in this report.

[2] Please note that IAI (2011) publishes a historical value of 24.4 million metric tons of carbon dioxide equivalent ($MtCO_2e$) for 2010.

[3] It should be noted that PFPB and CWPB are essentially same cell design, but with different alumina feed processes.

However, in practice, the greatest potential for reduction in PFC emissions is through addition of new greenfield PFPB capacity in concert with the shutdown of existing high emitting facilities.[4]

**Figure 7-1: PFC Emissions from Primary Aluminum Production: 2000–2030 ($MtCO_2e$)**



Source: U.S. Environmental Protection Agency (USEPA), 2012

Global abatement potential in the primary aluminum sector is 22 $MtCO_2e$ in 2030, which represents approximately 58% of the projected baseline emissions. Figure 7-2 shows the global marginal abatement cost (MAC) curves for 2010, 2020, and 2030.

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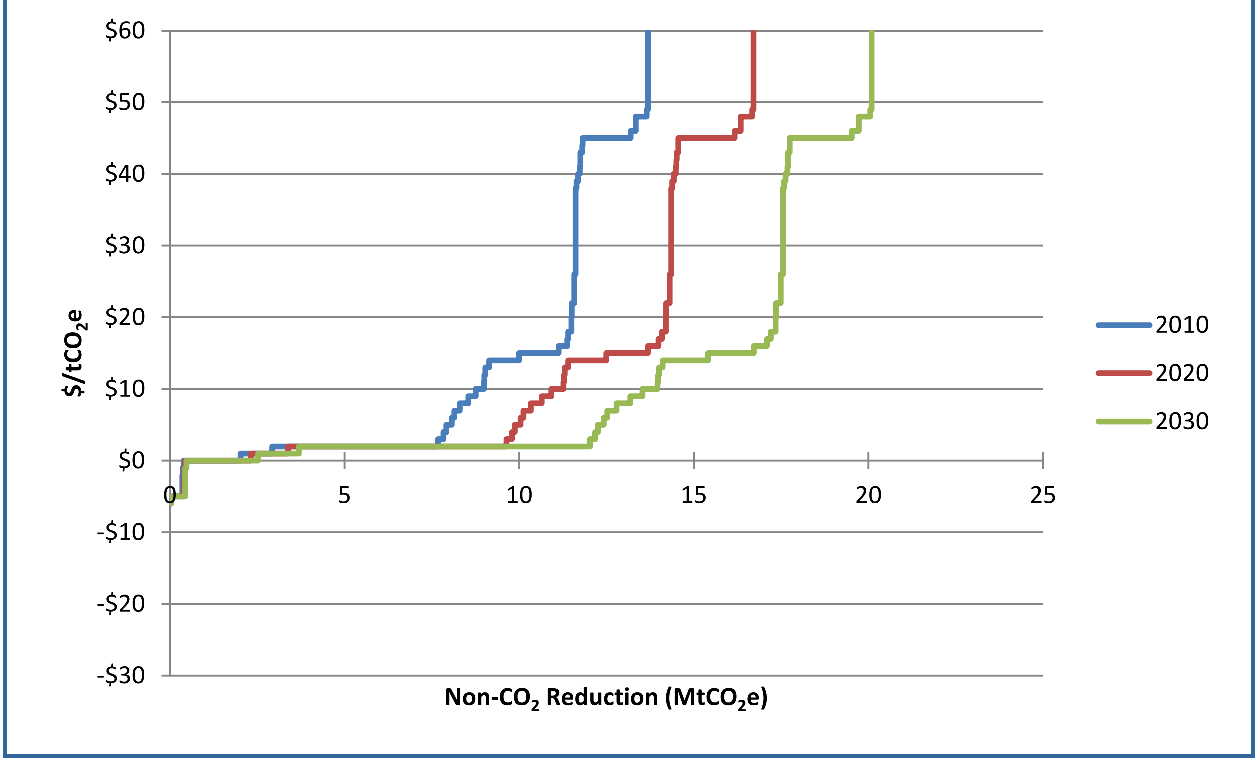
[4] More information on how global primary aluminum production according to cell type changed from 1990–2012 is available in “Figure 2: Primary aluminium smelting technology mix, 1990–2012” in *Results of the 2012 Anode Effect Survey: Report on the Aluminium Industry’s Global Perfluorocarbon Gases Emissions Reduction Programme*, International Aluminium Institute, London, United Kingdom. Available online at: http://www.world-aluminium.org/media/filer_public/2013/08/20/2012_anode_effect_survey_report.pdf.

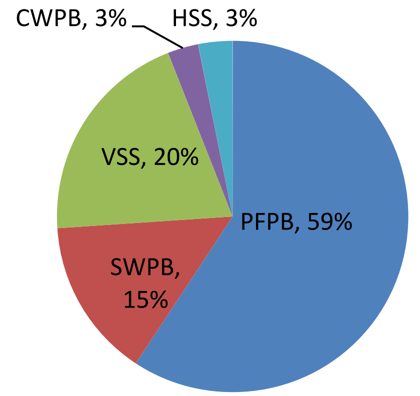
**Figure 7-2: Global Abatement Potential in Primary Aluminum Production: 2010, 2020, and 2030**



## IV.7.2 Emissions from Primary Aluminum Production

Emissions of the PFCs $CF_4$ and $C_2F_6$ from primary aluminum production are estimated using a variety of activity data (e.g., historical emissions, aluminum production, nameplate capacity), key growth assumptions (e.g., production growth rate, country-specific trends), and emission factors. Calculations of PFC emissions from this sector are based on historical and expected levels of aluminum production and reported (i.e., International Aluminium Institute [IAI]) emission factors from historical experience. Emissions factors vary by aluminum production technology (e.g., electrolytic cell type) and region (e.g., China, rest of the world). More information on the estimation methodology is available in the update to the Global Emission Report (USEPA, 2012). Figure 7-3 shows the percentage of total PFC emissions according to production technology type in 2020.

Figure 7-3: Global PFC Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



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For the purpose of developing the cost analysis, five different types of aluminum manufacturing facilities were considered, based on the technology types—VSS, HSS, SWPB, CWPB, and PFPB. Each model production facility analyzed produces 200,000 metric tons of aluminum annually.[5]

### IV.7.2.1 Activity Data and Important Trends

The main activity data used to estimate emissions from primary aluminum production are historical and projected, country-specific, annual, primary aluminum production estimates.

Historical, country-specific, primary aluminum production data for 2010 are compiled from data provide by the U.S. Geological Survey (USGS) in *Mineral Yearbook: Aluminum* (USGS, 2011a). In 2010, world primary aluminum production totaled approximately 40,800 thousand metric tons (USGS, 2011a).[6]

Projected, country-specific, primary aluminum production data for 2015, 2020, 2025, and 2030 are estimated based on a combination of either applying the global aluminum production compounded annual growth rate of 2.5% per year as reported by the Intergovernmental Panel on Climate Change (IPCC) (Martchek, 2006) to the 2010 country-specific production estimate, or for certain countries, specific

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[5] It should be noted that the nameplate capacities of newly-built PFPB facilities around the world are typically larger than 200,000 metric tons.

[6] It should be noted that the world primary aluminum production total for 2010 was revised from the value available at the time of the analysis for this report—40,800 thousand metric tons—to 41,200 thousand metric tons in 2011 Mineral Yearbook: Aluminum [Advance Release]. Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2011-alumi.pdf. Most of this increase was in India and Norway.

production projections provided in comments from the USGS (USGS, 2011b).[7] For countries with newly developed primary aluminum production (e.g., Qatar, Saudi Arabia) or newly re-commissioned primary production (e.g., Nigeria), the production projections are based on expected production capacity in future years. The country-specific aluminum production data described above is then disaggregated to cell technology type using primary aluminum smelting technology mix information derived from IAI's *2010 Anode Effects Survey Report* (IAI, 2011). For countries where future production is anticipated to be greater than the nameplate capacity in 2010, the excess production is assigned to PFPB technology. All current and future production in China is also assumed to be PFPB technology.

New primary aluminum production is increasingly taking place in emerging and developing regions, including China and the Middle East, and other countries, including Iceland, where there is the availability of long term, economically attractive power. New facilities open using new, less emissive PFPB technologies. In addition, over time older facilities, which use older, more emissive technologies, are likely to close, especially if they do not have continued access to competitive power (and labor) agreements. For example, China is anticipated to continue to be the major primary aluminum producer, and now uses PFPB technology across all of its facilities.[8] Other high-production countries use a mix of technology types, and production in some of these countries is anticipated to grow, while production in others is expected to remain constant. For example, after 2015, the United States is anticipated to no longer be a top five producer of primary aluminum. Thus, emissions in countries with new production are likely to grow more slowly than emissions from countries with existing production given similar increases in the rate of primary aluminum produced.

### IV.7.2.2 Emission Estimates and Related Assumptions

As previously mentioned, global emissions of PFCs from primary aluminum production are estimate as 26 $MtCO_2e$ in 2010, and are projected to grow to 37 $MtCO_2e$ in 2030. Emissions from aluminum production can generally be described in terms of historical emissions and projected emissions. Historical, global, PFC emissions data for 1990 through 2010 are compiled from data provided by the IAI in *2010 Anode Effects Survey Report* (IAI, 2011). Projected, country-specific, PFC emissions data for 2010 through 2030 are estimated based on the product of the country-specific production by cell technology type and the technology-specific mean emission factor for the respective year.

Table 7-1 shows the top countries and regional breakout of emissions of PFCs from primary aluminum production from 2010 to 2030.

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[7] It should be noted that growth rates in primary aluminum production have exceeded this value over the past decade—e.g., 5.3% this decade based on IAI statistics (see http://www.world-aluminium.org/statistics/primary-aluminium-production/#data)—and aluminum industry leaders have publically estimated growth rates of at least 5% in the foreseeable future. Growth rates in aluminum production have historically tracked GDP growth in developed countries, and aluminum growth rates have been historically greater than GDP growth in developing countries based on the need for aluminum in infrastructure and transportation development. In addition, production growth rates are region specific, and consumption is not driven by an average (mean) global GDP growth. Rather, aluminum demand is driven by fast growing economies, thus is more influenced by high growth GDP regions. Therefore, the published value of 2.5% available at the time of the analysis for this report is likely too small, even taking into account the current global slowdown. Out to 2020 and beyond, as China, India and other countries increasingly urbanize, this growth rate will likely further accelerate.

[8] It should be noted that while China has converted to PFPB technology, the country's cell designs and control strategies result in PFC emission factors great than those for PFPB technology operated in the rest of world (ROW). As a result, separate PFPB emission factors were applied for China versus ROW.

Table 7-1: Projected Baseline Emissions from Primary Aluminum Production: 2010–2030 ($MtCO_2e$)

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 11.1 | 12.6 | 14.3 | 16.2 | 18.3 | 2.5% |
| United States | 3.7 | 3.7 | 3.6 | 3.6 | 3.6 | −0.1% |
| Russia | 2.5 | 2.8 | 3.0 | 3.2 | 3.4 | 1.6% |
| Canada | 1.7 | 1.8 | 2.0 | 2.1 | 2.3 | 1.5% |
| Australia | 0.8 | 0.8 | 0.9 | 1.0 | 1.1 | 1.5% |
| **Rest of Regions** | | | | | | |
| Africa | 1.2 | 1.2 | 1.3 | 1.4 | 1.4 | 1.1% |
| Central & South America | 0.8 | 0.8 | 0.9 | 1.0 | 1.1 | 1.8% |
| Middle East | 1.2 | 1.8 | 1.9 | 2.0 | 2.0 | 2.6% |
| Europe | 1.8 | 1.9 | 2.1 | 2.3 | 2.4 | 1.5% |
| Eurasia | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 1.8% |
| Asia | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.6% |
| North America | — | — | — | — | — | — |
| **World Total** | **26.0** | **28.9** | **31.4** | **34.3** | **37.4** | **1.8%** |

[a] CAGR = Compound Annual Growth Rate

Source: USEPA, 2012

## IV.7.3 Abatement Measures and Engineering Cost Analysis

PFC emission reductions can primarily be achieved by installing/upgrading process computer control systems[9] and installing alumina point-feed systems.[10] The two abatement options considered for this analysis are (1) a minor retrofit involving the upgrade of process computer control systems only and (2) a major retrofit involving both the installation/upgrade of process computer control systems and the installation of alumina point-feed systems.[11] The installation of alumina point-feed systems is not analyzed on its own, because it would be very unlikely that an aluminum production facility would install alumina point-feed systems without also installing or upgrading process computer control systems.[12]

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[9] Process computer control systems control the repositioning of carbon anodes as they are consumed and provide greater control over raw material (alumina) feeding. All smelters operate with process control computers. The upgrade would involve changes in the algorithms controlling feed and anode effect detection.

[10] Point-feed systems allow more precise alumina feeding.

[11] A major retrofit results in PFPB technology, which is the state-of-the-art technology in aluminum production. Conversion to PFPB technology results in the most reliable increases in operational and production efficiency; although the capital outlay for this option is significant. In addition, retrofit options are usually implemented after extensive computer modeling and large-scale development work is conducted on test cells.

[12] It should be noted that, as previously mentioned, existing, older, and higher PFC emitting systems can further improve their anode effect performance by implementing management and work practices, as well as improved control software.

### IV.7.3.1 Minor Retrofit

A minor retrofit involves the installation/upgrade of process computer control systems. Minor retrofits can be performed at any facility type other than the state-of-the-art PFPB facilities. For the purpose of the cost analysis, a minor retrofit has a lifetime of 10 years for VSS, HSS, and SWPB facility types; 20 years at the CWPB facility; and 30 years at the PFPB facilities, based on expert judgment. The lifetime of the minor retrofit at older facilities is shorter because the estimated remaining lifetime of the facilities themselves is shorter.

- **Capital Costs:** Capital costs represent the costs associated with purchasing and installing the process computer control systems at the aluminum production facilities. The capital costs, obtained from International Energy Agency (IEA) (2000) and confirmed by Marks (2011a), range from $6 million to $8 million (2010 USD), depending on the facility type.
- **Annual O&M Costs:** The annual O&M costs associated with the retrofits are strictly the additional operating costs for the increased aluminum production. The additional operating costs were assumed to equal the percentage increase in current efficiency multiplied by the capital costs of the retrofit, which is the method used to estimate O&M costs by IEA (2000). These costs range from approximately $60,000 to $120,000 (2010 USD), depending on the facility type.
- **Annual Revenue:** Based on expert judgment, it is assumed that the increased current efficiency (aluminum production/unit of electricity) resulting from the retrofits would be used by the model facilities to produce more aluminum with the same amount of electricity consumption as before (rather than producing the previous levels of aluminum production and realizing the electricity savings).[13] Consequently, additional revenues of approximately $0.5 million to $1 million (2010 USD) are associated with the minor retrofit option, depending on the facility type.
- **Technical Lifetime**: The expected lifetime range is assumed to be 10 years for VSS, HSS, and SWPB facility types. Longer lifetimes of 20 and 30 years are applied to CWPB and PFPB facility types, respectively.
- **Reduction Efficiency**: The minor retrofits reduction efficiency varies by facility type (see Table 7-2).

**Table 7-2: Primary Aluminum Production Abatement Options**

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **Minor retrofit** | 24%–55% | All facility types other than state-of-the-art PFPB facilities |
| **Major retrofit** | 77%–96% | VSS, HSS, SWPB facilities |

### IV.7.3.2 Major Retrofit

A major retrofit involves both the installation/upgrade of process computer control systems and the installation of alumina point-feed systems. A major retrofit results in AE performance approaching that of PFPB technology, which is the state-of-the-art technology in aluminum production. A major retrofit also results in increases in operational and production efficiency, although the capital outlay for this option is significant. In addition, retrofit options are usually implemented after extensive computer modeling and large-scale development work are conducted on test cells. Major retrofits can be performed

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[13] Note that this is a simplifying assumption for the purpose of this analysis; any increase in production would be driven by demand for aluminum, not specifically driven by a set level of electricity consumption.

for the older facility types (VSS, HSS, and SWPB). According to Marks (2011b), there is no opportunity for conventional CWPBs to install point feeders because they already have "bar break" feed systems, which have roughly the same anode effect performance as point feeders; and by definition, a PFPB model facility has point-feeding systems, so there is no opportunity for additional application.

For the purpose of the cost analysis, a major retrofit has a lifetime of 10 years, based on expert judgment.

- **Capital Costs:** Capital costs represent the costs associated with purchasing and installing the process computer control systems and alumina point-feeding technologies at the aluminum production facilities. The capital costs, obtained from IEA (2000) and confirmed by Marks (2011a), range from $12 million to $90 million (2010 USD), depending on facility type.
- **Annual Operation and Maintenance (O&M) Costs:** The annual O&M costs associated with the retrofits are strictly the additional operating costs for the increased aluminum production. The additional operating costs were assumed to equal the percentage increase in current efficiency multiplied by the capital costs of the retrofit, which is the method used to estimate O&M costs by IEA (2000), and range from $350,000 to $3.4 million (2010 USD), depending on facility type.
- **Annual Revenue:** Based on expert judgment, it is assumed that the increased current efficiency (aluminum production/unit of electricity) resulting from the retrofits would be used by the model facilities to produce more aluminum with the same amount of electricity consumption as before (rather than producing the previous levels of aluminum production and realizing the electricity savings). Increased current efficiencies for each facility and retrofit are available from IEA (2000). For a major retrofit, these revenues range from $1 million to $2 million (2010 USD), depending on facility type.
- **Technical Lifetime:** The expected lifetime of this technology is 10 years.
- **Reduction Efficiency:** This analysis assumes a reduction efficiency of 78% for HSS, 96% for SWPB, and 77% for VSS facilities.

### IV.7.3.3 Engineering Cost Data Summary

Table 7-3 presents the engineering cost data for each abatement measure outlined above, including all cost parameters necessary to calculate the break-even price.

## IV.7.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the primary aluminum production sector.

Table 7-3: Engineering Cost Data on a Facility Basis

| Abatement Option | Facility Type | Project Lifetime (Years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| **Minor retrofit** | VSS | 10 | $5,980,801 | $1,019,402 | $119,616 | 21,277 |
| | HSS | 10 | $5,980,801 | $509,701 | $59,808 | 112,894 |
| | SWPB | 10 | $6,238,348 | $764,552 | $93,575 | 41,900 |
| | CWPB | 20 | $7,125,452 | $509,701 | $71,255 | 83,800 |
| | PFPB | 30 | $8,026,865 | $509,701 | $80,269 | 129,607 |
| **Major retrofit** | VSS | 10 | $84,546,778 | $2,038,805 | $3,381,871 | 112,894 |
| | HSS | 10 | $89,039,533 | $1,019,402 | $1,780,791 | 41,900 |
| | SWPB | 10 | $11,804,213 | $1,529,104 | $354,126 | 83,800 |

### IV.7.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous Section 7.3 of this chapter at the five model facilities to calculate a break-even price for the applicable options at each facility.

### IV.7.4.2 Definition of Model Facilities

As mentioned at the beginning of this chapter, five different electrolytic cell types are used to produce aluminum—VSS, HSS, SWPB, CWPB, and PFPB, which is considered the most technologically-advanced process to produce aluminum.

A facility's performance may be represented by the mean or median (depending on the size of the cohort of facilities and the range of performance) PFC emission factor—PFC emissions per unit production (e.g., metric tons $CO_2e$/metric ton Al)—for a particular cell technology type. However, in the case of PFPB technology, the universe of facilities using this technology is further subdivided into state-of-the-art (i.e., newer) PFPB facilities for which no abatement measures are applicable and other (i.e., older) PFPB facilities for which certain abatement measures are an option. The performance for state-of-the-art (as opposed to other) PFPB technology is therefore better represented by a PFC emission factor less than the average (i.e., the median). Table 7-4 presents a description of the model facilities considered for this analysis.

### IV.7.4.3 Assessment of Technical Effectiveness

To assess the abatement potential from each technology option, one additional parameter is needed, which is termed the technical effectiveness. The technical effectiveness parameter determines the share of emissions reductions attributed to each abatement measure. Similar to other industrial process sectors covered in this report, the technical effectiveness parameter is defined as the percentage of emissions reductions achievable by each technology/facility combination. Estimating this parameter requires assumptions regarding the distribution of emissions by manufacturing process (i.e., VSS, HSS, SWPB, CWPB, and PFPB) in addition to process-specific estimates of technical applicability and market penetration. The technical applicability, market penetration, and reduction efficiency assumptions are held constant for all model years. Table 7-5 reports the technical applicability parameters estimated of each abatement measure/facility type combination. Table 7-5 also presents the market penetration,

Table 7-4: Description of Primary Aluminum Production Facilities

| Facility Type | Description |
|---|---|
| **VSS** | This facility uses VSS technology, with an average PFC emission factor of 1.01 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year. |
| **HSS** | This facility uses HSS technology, with an average PFC emission factor of 1.07 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year. |
| **SWPB** | This facility uses SWPB technology, with an average PFC emission factor of 5.41 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year. |
| **CWPB** | This facility uses CWPB technology, with an average PFC emission factor of 0.51 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year. |
| **PFPB (state of the art)** | This facility uses state-of-the-art PFPB technology, with a median PFC emission factor of 0.23 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year. |
| **PFPB (other)** | This facility uses other PFPB technology, with an average PFC emission factor of 0.51 metric tons $CO_2$e/metric ton Al. The production capacity of the facility is 200,000 metric tons per year.[a] |

[a] It should be noted that "state of the art" has been improving rapidly with respect to anode effect performance and the best PFPB facilities (top 10%) are performing at better than 0.06 metric tons $CO_2$e/metric ton Al. Median performance for all IAI non-Chinese producers is about 0.23 metric tons $CO_2$e/metric ton Al, while median Chinese PFPB performance is about 0.7 metric tons $CO_2$e/metric ton Al.

Table 7-5: Technical Effectiveness Summary

| Abatement Option | Model Facility Type | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
|---|---|---|---|---|---|
| **Minor retrofit** | | | | | |
| | VSS | 27% | 100% | 39% | **11%** |
| | HSS | 100% | 50% | 39% | **20%** |
| | SWPB | 100% | 50% | 24% | **12%** |
| | CWPB | 100% | 100% | 55% | **55%** |
| | PFPB | 100% | 100% | 55% | **55%** |
| **Major retrofit** | | | | | |
| | VSS | 73% | 100% | 77% | **56%** |
| | HSS | 100% | 50% | 78% | **39%** |
| | SWPB | 100% | 50% | 96% | **48%** |

technical applicability, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameter. Technical effectiveness is equal to the product of the technical applicability, market penetration, and reduction efficiency.

Technical applicability factor for VSS is based on the assumption that roughly 27% of VSS capacity already has point feeding (Marks, 2011b). This percentage is described in more detail in Appendix I.

### IV.7.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.7.3 to calculate the break-even price for each mitigation option/facility combination. Table 7-6 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

**Table 7-6: Example Break-Even Prices for Abatement Measures in Primary Aluminum Production**

| Abatement Option | Model Facility Type | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($/$tCO_2e$) | Net Annual Cost ($/$tCO_2e$) | Tax Benefit of Depreciation ($/$tCO_2e$) | Break Even Price ($/$tCO_2e$) |
|---|---|---|---|---|---|---|
| **Minor retrofit** | | | | | | |
| | VSS | 21,277 | $76 | −$42 | $19 | **$4** |
| | HSS | 41,900 | $39 | −$11 | $10 | **$9** |
| | SWPB | 129,607 | $13 | −$5 | $3 | **$2** |
| | CWPB | 56,667 | $25 | −$8 | $4 | **$13** |
| | PFPB | 56,087 | $25 | −$8 | $3 | **$14** |
| **Major retrofit** | | | | | | |
| | VSS | 112,894 | $203 | $12 | $50 | **$120** |
| | HSS | 83,800 | $288 | $9 | $71 | **$113** |
| | SWPB | 518,429 | $6 | −$2 | $2 | **$1** |

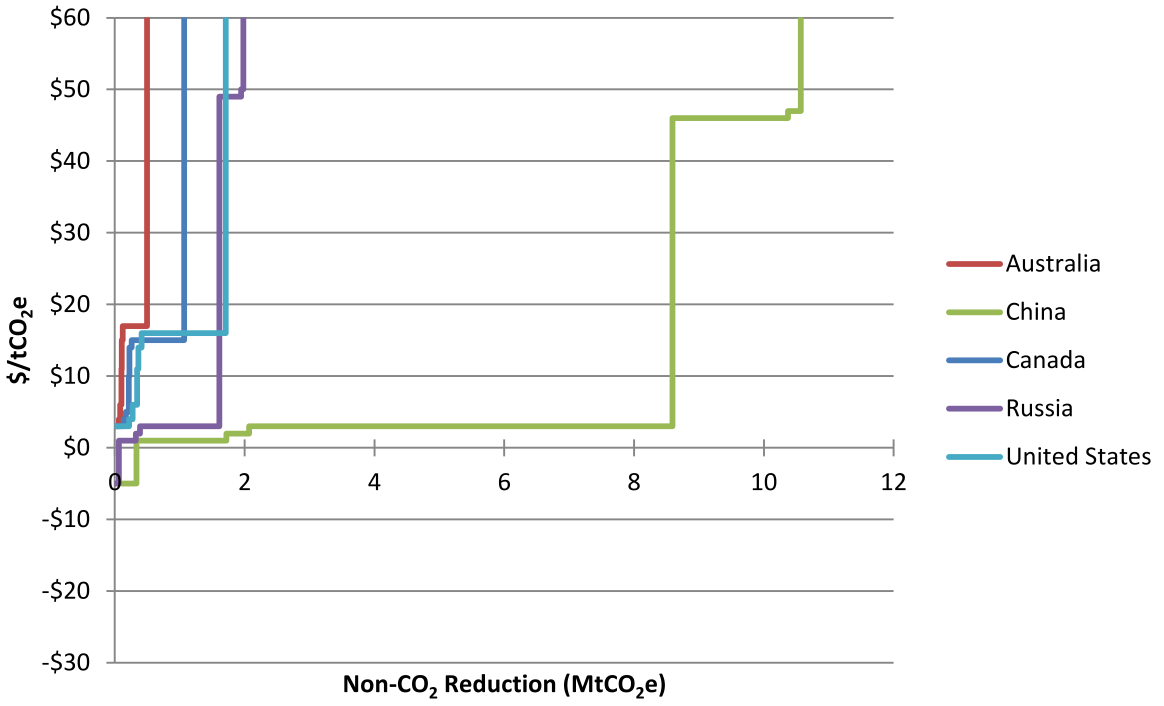
## IV.7.4.5 MAC Analysis Results

The global abatement potential for PFC emissions in the primary aluminum production sector is 22 $MtCO_2e$, which is approximately 58% of total projected emissions in 2030. Table 7-7 presents the cumulative reductions achieved at selected break-even prices. Figure 7-4 shows the MAC curve for the top five emitting countries and the rest of world.

**Table 7-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break Even Price ($/$tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | 10 | 5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| Australia | — | — | — | 0.1 | 0.1 | 0.1 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 |
| Canada | — | — | — | 0.21 | 0.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.3 |
| China | — | 0.3 | 1.7 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 10.6 | 10.6 | 10.6 |
| Russia | — | 0.1 | 0.3 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 2.0 | 2.0 | 2.0 |
| United States | — | — | — | 0.34 | 0.4 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 2.1 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | 0.0 | 0.3 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 |
| Central and South America | — | — | 0.0 | 0.2 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.6 |
| Middle East | — | — | 0.0 | 0.2 | 0.4 | 0.8 | 0.9 | 0.9 | 0.9 | 1.0 | 1.2 |
| Europe | — | — | 0.0 | 0.2 | 0.6 | 0.8 | 0.9 | 1.1 | 1.1 | 1.3 | 1.4 |
| Eurasia | — | 0.0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Asia | — | — | 0.0 | 0.1 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 |
| North America | — | — | — | — | — | — | — | — | — | — | — |
| **World Total** | **—** | **0.43** | **2.53** | **12.4** | **14.0** | **16.7** | **17.3** | **17.5** | **20.1** | **20.5** | **21.6** |

**Figure 7-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030**



## IV.7.4 Uncertainties and Limitations

The emission projections (i.e., baseline emissions) account for the historical reduction in the effective emission factor (i.e., metric ton $CO_2e$/metric ton Al) realized by facilities, but do not assume that aluminum producers have conducted retrofits, or will continue to introduce technologies and practices aimed at reducing PFC emissions. That said, the global primary aluminum industry through the IAI has a voluntary PFC emission reduction goal of reduce emissions of PFCs per metric ton of aluminum by at least 50% by 2020 as compared to 2006 (IAI, 2013). In addition, commissioning of new—less emissive—facilities to meet global demand will also have the result of reducing the effective emission factor.

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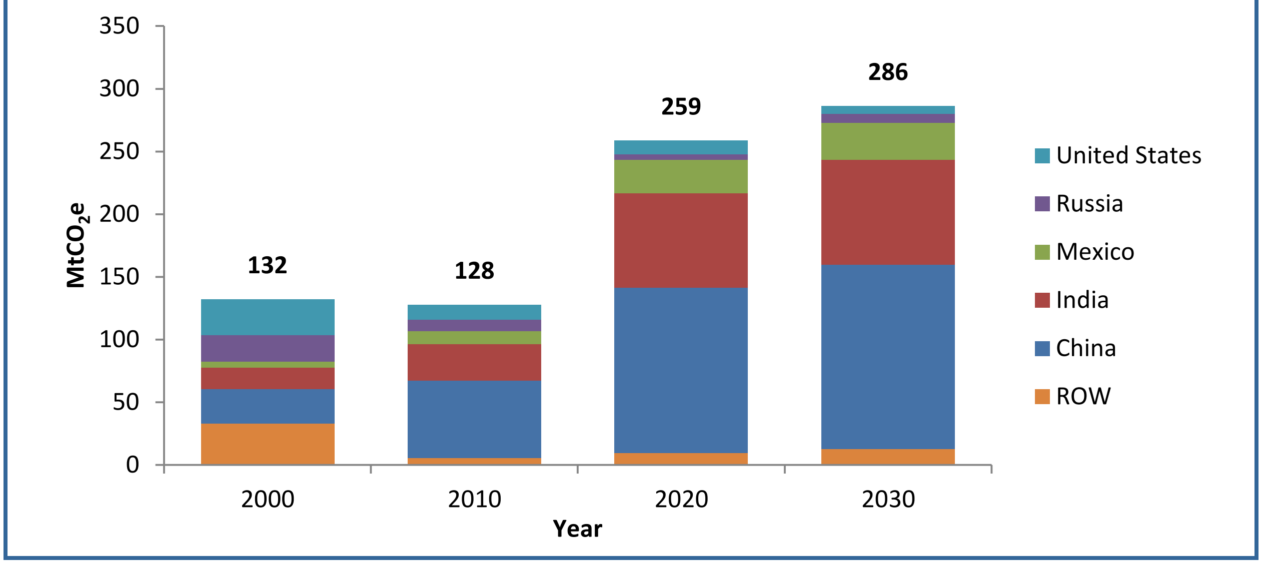
# IV.8. HFC-23 Emissions from HCFC-22 Production

## IV.8.1 Sector Summary

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

Global HCF-23 emissions are projected to more than double, growing from 127.9 million metric tons of carbon dioxide equivalent (MtCO$_2$e) in 2010 to 286.4 MtCO$_2$e in 2030. Figure 8-1 shows the projected changes in annual emissions of HFC-23 out to year 2030. China, India, and Mexico are projected to see the largest increases in HFC-23 emissions primarily because of increased HCFC-22 production capacity in these countries.

Figure 8-1: HCF-23 Emissions from HCFC-22 Production: 2000–2030 (MtCO$_2$e)



Source: U.S. Environmental Protection Agency (USEPA), 2012

The production of HCFC-22 in developed countries has decreased in the last decade, while growth of annual HCFC-22 production in developing countries has grown substantially, driven primarily by the demand for its use as feedstock in fluoropolymer manufacture (Montzka et al., 2010). All HCFC-22 producers in developed countries have implemented either process optimization and/or thermal destruction to reduce HFC-23 emissions. In a few cases, HFC-23 is collected and used as a substitute for Ozone Depleting Substances (ODSs), mainly in very-low temperature refrigeration and air-conditioning systems.[1] Several HCFC-22 production facilities in developing countries participate in the United Nations

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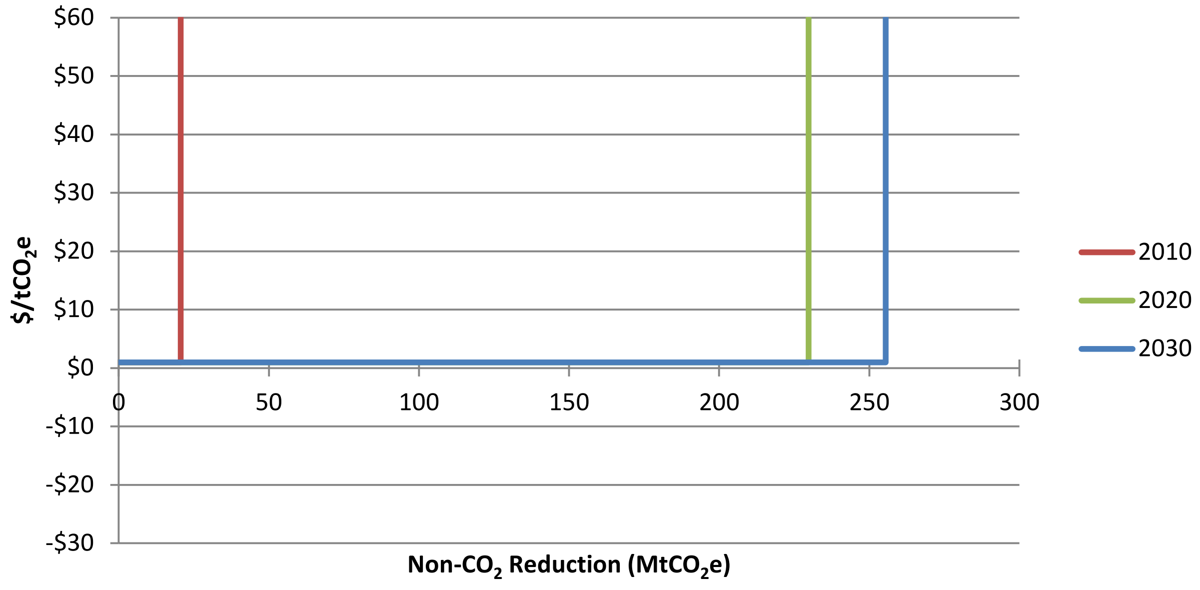
[1] Emissions from this use are quantified in the air conditioning and refrigeration chapters and are therefore not included here.

Framework on Climate Change's Clean Development Mechanism (CDM) and through their destruction of coproduced HFC-23, they are eligible for Certified Emission Reduction (CER) credits. Such projects were approved beginning in 2003, and although currently 19 projects are approved, a large fraction of facilities producing HCFC-22 in developing countries are not CDM participants, in part because not all HCFC-22 facilities are eligible to earn credits under CDM. Current CDM rules state that HCFC-22 production facilities must have an operating history of at least three years between January 2000 and December 2004 in order to be eligible for a project. A study published in 2010 reported that approximately 57 percent of HCFC-22 were produced but not covered by existing CDM projects (Montzka et al., 2010). In another assessment, approximately 43 production lines within 26 existing HCFC-22 facilities were identified in Article 5 countries. There are about 23 production lines within 17 facilities in Article 5 countries with CDM Projects approved or awaiting approval (Hufford et al., 2012).

This analysis examines the costs to mitigate HFC-23 emissions from HCFC-22 production plants that do not have incineration technology installed and the costs to mitigate HFC-23 emissions from those facilities that have thermal destruction devices installed because of a CDM project but are assumed not to choose to continue their operation after the CDM crediting period expires. There is uncertainty regarding the future of HFC-23 CDM projects and compliance carbon markets in general; the assumptions chosen to develop projected abatement potential in this analysis represent one potential scenario. A discussion regarding the limitations of this analysis is presented in Section IV.8.4

Global mitigation potential of HFC-23 from HCFC-22 production in 2030 is 255 $MtCO_2e$, roughly 89% of the projected baseline emissions. Figure 8-2 presents the sector marginal abatement cost (MAC) curves for 2010, 2020, and 2030. This analysis examines the abatement option employed by production facilities to destroy HFC-23—installation and/or operation of thermal oxidation devices; as shown in the figure, abatement can be achieved at a low break-even price between \$0/$tCO_2e$ and \$1/$tCO_2e$.

**Figure 8-2: Global Abatement Potential in HCFC-22 Production: 2010, 2020, and 2030**



### IV.8.1.1 Emissions from HCFC-22 Production

In the production of HCFC-22, HFC-23 is separated as a vapor from the condensed HCFC-22, and emissions occur through venting of HFC-23 to the atmosphere as an unwanted by-product.

For the purpose of evaluating the cost of reducing HFC-23 emissions from HCFC-22 production, this analysis considers reduction costs for a typical HCFC-22 production facility, characterized as having a production capacity of approximately 22,400 metric tons of HCFC-22 (the average production capacity of all HCFC-22 production plants) and HCFC-22 production at 82% of that production capacity based on production estimates (Will et al., 2004; 2008).

Additionally, this analysis considers several possibilities for the level of abatement technology used at the typical HCFC-22 production facility, reflecting different levels of emissions. The analysis examines four possible categories of facilities. The first two categories address current and historical levels of emissions from current facilities:

1. *Facilities with abatement controls in place already.* This level of abatement is true for all production facilities in the Annex I countries and facilities that have CDM projects. Since the start of Clean Development Mechanism (CDM) projects for HCFC-22 production, there have been 19 CDM projects; the majority of these projects are at HCFC-22 production facilities in China (11 in total), followed by India (5), Argentina (1), Mexico (1), and the Republic of Korea (1).
2. *Facilities with no abatement technology controls installed.* Such facilities currently exist in China and Venezuela.

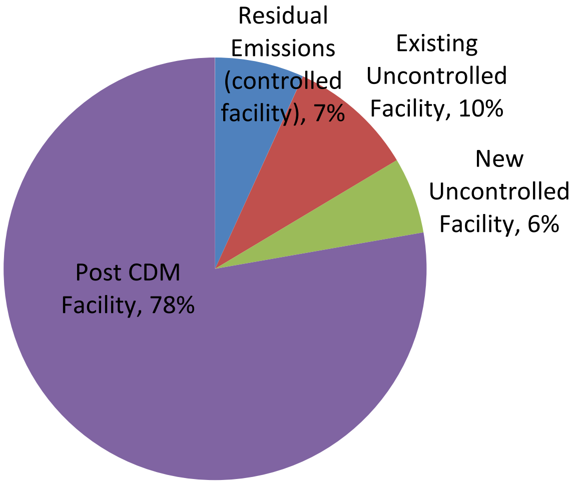
The third and fourth facility categories assist in projecting future emissions from current and new facilities:

1. *New facilities entering the market.* To meet future global demand of HCFC-22, the analysis estimates new facilities to enter the market once projected production for a non-Annex country exceeds current capacity of the facilities within the country. New facilities are characterized as being built without control technology.
2. *Facilities having previously participated in a CDM project, but not currently incinerating.* When a CDM crediting period is over and the CDM project is completed, this analysis assumes that the incineration device installed as a result of the CDM project will not be kept in operation. The cost assumptions for these facilities differ from those of a new uncontrolled facility in that no capital costs will be needed to install the incinerator. This analysis assumes that all facilities participating in CDM have completed their crediting periods by 2020.

### IV.8.1.2 Activity Data or Important Sectoral or Regional Trends

The primary activity data for HFC-23 emissions from this sector are the level of HCFC-22 production in the country and whether the production uses any HFC-23 abatement. A total of 20 countries produce HCFC-22, and of this total, only 12 countries are assumed to continue to produce HCFC-22 between 2015 and 2030. Regionally, abatement of HFC-23 emissions is occurring in developed countries, and in developing countries, abatement is driven by the CDM incentives for HFC-23 abatement. Thus, the most significant regional trends are driven by assumptions about the extent to which abatement is occurring by country and whether that abatement will continue in the future. Overall, global HCFC-22 production is assumed to continue to grow at a modest rate to meet the demand of HCFC-22 use for feedstock in fluoropolymer manufacturing, despite restrictions on HCFC-22 production for dispersive uses of HCFC-22 in response to the controls of HCFC-22 consumption under the Montreal Protocol. Figure 8-3 shows the projected distribution of global HFC-23 emissions by facility type in 2020.

**Figure 8-3: Global HFC-23 Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)**



### IV.8.1.3 Emission Estimates and Related Assumptions

Emissions of HFC-23 from HCFC-22 production were estimated to be 127.9 MtCO$_2$e in 2010, growing to 286.4 MtCO$_2$e in 2030. Table 8-1 presents the projected annual HFC-23 emissions between 2010 and 2030 for the top five emitting countries and rest of global regions.

**Table 8-1: Projected Baseline Emissions from HCFC-22 Production: 2010–2030 (MtCO$_2$e)**

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010 2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 62.1 | 70.0 | 132.2 | 142.3 | 147.0 | 4.4% |
| India | 29.1 | 37.3 | 75.2 | 80.9 | 83.6 | 5.4% |
| Mexico | 10.2 | 13.1 | 26.5 | 28.5 | 29.4 | 5.4% |
| Russia | 9.3 | 6.9 | 4.6 | 5.9 | 7.5 | -1.1% |
| United States | 11.8 | 10.6 | 10.8 | 7.9 | 6.0 | -3.3% |
| **Rest of Region** | | | | | | |
| Africa | — | — | — | — | — | — |
| Central & South America | 2.5 | 2.8 | 3.7 | 4.0 | 4.1 | 2.6% |
| Middle East | — | — | — | — | — | — |
| Europe | 1.0 | 1.0 | 1.1 | 1.4 | 1.8 | 2.9% |
| Eurasia | — | — | — | — | — | — |
| Asia | 1.9 | 2.4 | 4.7 | 5.4 | 6.8 | 6.7% |
| North America | — | — | — | — | — | — |
| **World Total** | **127.9** | **144.2** | **258.8** | **276.3** | **286.4** | **4.1%** |

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

To estimate historical emissions of HFC-23, dispersive and feedstock HCFC-22 production levels were developed and subsequently multiplied by a HFC-23/HCFC-22 coproduction ratio (i.e., tons of HFC-23 emitted per ton of HCFC-22 produced). To account for thermal abatement technologies in the baseline, the analysis used a lower HFC-23/HCFC-22 production ratio. Depending on how well the process is optimized, these ratios can range from 1.4% to 4% (Rotherham, 2004; McCulloch and Lindley, 2007). The emission rate for Annex I countries was assumed to be 2% across the entire time series (Montzka et al., 2010). The emission rate for non-Annex I countries and Russia was assumed to be 3% from 1990 through 2005 (USEPA, 2006) and 2.9% from 2006 through 2007 (Miller et al., 2010). The lower emission rate takes into account any HFC-23 emission offsets from CDM projects in these countries and the Joint Implementation (JI) project at Russia's HCFC-22 plant in Perm. Where UNFCCC-reported HFC-23 emission estimates were available through the UNFCCC flexible query system, these estimates were used in place of estimates calculated using production data (UNFCCC, 2009).

HFC-23 emission projections were developed for Annex I countries including Germany, Japan, the Netherlands, Russia, Spain, and the United States. For the United States, National Communications projections of emissions were used for 2010 to 2020 (UNFCCC, 2009); emissions trends were used to project HFC-23 emissions for the remainder of the time series (2025 through 2030). For all other Annex I countries, the dispersive production and feedstock production portion of emissions were projected separately to account for the decline in the production for dispersive purposes because of the phaseout requirements of the Montreal Protocol. To project the feedstock production portion of HFC-23 emissions, USEPA applied the 5% global growth rate of feedstock HCFC-22 production as reported in Montzka et al. (2010).

HFC-23 emission projections were developed for non-Annex I countries including China, India, Mexico, South Korea, and Venezuela. To do so, non-Annex I aggregate HCFC-22 production was projected for both dispersive and feedstock production; the production was then disaggregated by country using the percentage of each country's contribution to 2007 non-Annex I HCFC-22 production. Each country's HCFC-22 projected production was then apportioned into four different model facilities for each developing country, and two HFC-23/HCFC-22 coproduction ratios were applied to develop emission estimates—to address the varying use of abatement technologies by facilities. Table 8-2 presents the assumed distribution of baseline emissions by model facility and country/country group over time.

**Table 8-2: Distribution of HCF-23 Emissions by Location and Facility Type: 2010–2030**

| Country/Group | Model Facility Type | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| **Annex I** | Residual emissions | 100% | 100% | 100% | 100% | **100%** |
| **Annex I** | Non-CDM and uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **Annex I** | New uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **Annex I** | Post-CDM facility | 0% | 0% | 0% | 0% | **0%** |
| **Argentina** | Residual emissions | 100% | 100% | 0% | 0% | **0%** |
| **Argentina** | Non-CDM and uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **Argentina** | New uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **Argentina** | Post-CDM facility | 0% | 0% | 100% | 100% | **100%** |
| **China** | Residual emissions | 68% | 68% | 0% | 0% | **0%** |
| **China** | Non-CDM and uncontrolled facility | 32% | 32% | 17% | 16% | **15.9%** |
| **China** | New uncontrolled facility | 0% | 0% | 0% | 6% | **8.8%** |
| **China** | **Post-CDM facility** | **0%** | **0%** | **83%** | **78%** | **75.2%** |

(continued)

**Table 8-2: Distribution of HCF-23 Emissions by Location and Facility Type: 2010–2030 (continued)**

| Country/Group | Model Facility Type | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| **India** | Residual emissions | 100% | 78% | 0% | 0% | **0%** |
| **India** | Non-CDM and uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **India** | New uncontrolled facility | 0% | 22% | 14% | 20% | **22.6%** |
| **India** | Post-CDM facility | 0% | 0% | 86% | 80% | **77.4%** |
| **Mexico** | Residual emissions | 100% | 78% | 0% | 0% | **0%** |
| **Mexico** | Non-CDM and uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **Mexico** | New uncontrolled facility | 0% | 22% | 14% | 20% | **22.6%** |
| **Mexico** | Post-CDM facility | 0% | 0% | 86% | 80% | **77.4%** |
| **South Korea** | Residual emissions | 0% | 0% | 0% | 0% | **0%** |
| **South Korea** | Non-CDM and uncontrolled facility | 0% | 0% | 0% | 0% | **0%** |
| **South Korea** | New uncontrolled facility | 0% | 11% | 14% | 20% | **22.6%** |
| **South Korea** | Post-CDM facility | 100% | 89% | 86% | 80% | **77.4%** |
| **Venezuela** | Residual emissions | 0% | 0% | 0% | 0% | **0%** |
| **Venezuela** | Non-CDM and uncontrolled facility | 100% | 89% | 86% | 80% | **77.4%** |
| **Venezuela** | New uncontrolled facility | 0% | 11% | 14% | 20% | **22.6%** |
| **Venezuela** | **Post-CDM facility** | **0%** | **0%** | **0%** | **0%** | **0%** |

## IV.8.2 Abatement Measures and Engineering Cost Analysis

One abatement option, thermal oxidation, is examined in this analysis of the HCFC-22 production sector; Table 8-3 and Table 8-4 provide a technology overview of this abatement measure. For more detailed information on the abatement measures considered for this sector see Appendix J.

**Table 8-3: HCFC-22 Production Abatement Options**

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **Thermal Oxidation** | 95% | Facilities with no abatement technology controls installed |
| | | New facilities entering the market |
| | | Facilities having previously participated in a CDM project |

**Table 8-4: Engineering Cost Data on a Facility Basis**

| Facility Type | Project Lifetime (years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|
| **Facilities with no abatement technology controls installed** | 20 | $4,800,000 | $0 | $119,000 | **5,932,661** |
| **New facilities entering the market** | | $3,700,000 | | | |
| **Facilities having previously participated in a CDM project** | | **$0** | | | |

### IV.8.2.1 Thermal Oxidation

Thermal oxidation, the process of oxidizing HFC-23 to $CO_2$, hydrogen fluoride, and water, is a demonstrated technology for the destruction of halogenated organic compounds. For example, destruction of more than 99% of HFC-23 can be achieved under optimal conditions (i.e., a relatively concentrated HFC-23 vent stream with a low flow rate) (Rand et al., 1999). In practice, actual reductions will be determined by the fraction of production time that the destruction device is actually operating. Units may experience some downtime because of the extreme corrosivity of hydrogen fluoride and the high temperatures required for complete destruction. This analysis assumes a reduction efficiency of 95%.[2]

The destruction of HFC-23 by thermal oxidation is assumed to be 100% applicable to all facilities, and the analysis assumes a project lifetime of 20 years. Cost estimates for installing and operating a thermal oxidizer are summarized below:[3]

- **Capital Costs:** The capital cost for a thermal oxidation system is estimated to be approximately $4.8 million to install at an existing plant and $3.7 million to install as part of constructing a new plant (Irrgang, 2011).
- **Annual O&M Costs:** O&M costs are approximately 2% to 3% of total capital costs (Irrgang, 2011). This analysis assumes an annual cost that is 2.5% of total capital costs for facilities with no abatement technology control installed and just over 3% of total capital costs for new facilities that are entering the market.
- **Annual Revenue:** No annual savings or revenues are associated with the thermal oxidation abatement option.[4]
- **Technical Lifetime:** 20 years
- **Reduction Efficiency:** Thermal oxidation technology is assumed to be 95% efficient in abating HFC-23 emissions.

### IV.8.2.2 Evaluation of Future Mitigation Options and Trends

This analysis evaluates how thermal oxidation can be applied to facilities that are current CDM participants after the crediting period is over and the CDM project is completed. Because an incineration device is already installed as a result of the CDM project, the costs to adopt the abatement measure relate only to its annual operation. Facilities participating in CDM are assumed to have completed their crediting periods by 2020.

This analysis also assumes that new facilities will enter the market to meet future global demand of HCFC-22. New facilities are assumed to enter the market once projected production for a non-Annex I country exceeds current plant capacities. According to industry, the costs of installing thermal oxidation systems in new plants are generally less expensive than the cost of installation at existing plants. This

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[2] A representative of a company that manufactures thermal oxidation systems stated that new systems are built using materials that better resist corrosion than the materials used in older systems. The representative indicated that such new systems were likely to experience very limited downtime, considerably less than 5% (Rost, 2006).

[3] Estimates developed for this analysis are based on communication with industry and best available industry assessments; actual costs of some systems could differ from these estimates.

[4] It should be noted that annual revenue is generated for participants of CDM projects; however, CDM projects are not assumed to be covering further abatement of emissions in this analysis.

analysis uses a capital cost for new facilities that is approximately 23% less than the cost of installation at existing facilities (Irrgang, 2011).

## IV.8.3 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for HCFC-22 production sector.

### IV.8.3.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at the three model facility types to calculate a break-even price for each option at each facility. As mentioned earlier, this analysis developed four potential model facilities to model the mitigation potential in this sector. These facilities included the following:

- **Residual Emissions:** These are facilities that have abatement controls in place already. All facilities in the Annex I countries and facilities that have CDM projects (mitigation projects funded by developed countries under the Kyoto Protocol) in the developing countries are considered “residual emission facilities.”
- **Non-CDM and Uncontrolled Facility:** Non-CDM facilities are existing facilities that are uncontrolled. These facilities exist in China, South Korea, and Venezuela.
- **New Uncontrolled Facility:** New facilities are assumed to be uncontrolled when built. It is assumed that a new facility enters the market once projected production exceeds current capacity. In other words, the percentage of emissions from new facilities is 0% until projected production exceeds capacity. It is assumed that new facilities will only be built in non-Annex I countries.
- **Post-CDM Facility:** Similar to the “less mitigation scenario” of Miller et al. (2011), this analysis assumes that the 12 CDM projects that opted for a 7-year crediting period (in China, South Korea, Mexico, and Argentina) are not renewed after their first terms (note the remaining seven facilities opted for a one-time fixed crediting period that cannot exceed 10 years). Please see Section IV.8.4 for a discussion on the uncertainty and limitations regarding this assumption. Under this assumption, by 2020, all facilities previously controlled via CDM (“residual emission model facility”) are considered a “post-CDM” facility. It is assumed that the incineration device installed (via a CDM project) will not be kept in operation once the CDM crediting period is over. This analysis costs out mitigation from these facilities differently than a new uncontrolled facility by taking into account that no capital costs will be needed to install the incinerator.

### IV.8.3.2 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility type combination. Market penetration rates vary over time as systems are upgraded in the future. Table 8-5 summarizes the assumptions regarding technical applicability, market penetration, and technical effectiveness of thermal oxidation for each facility type.

**Table 8-5: Technical Effectiveness Summary**

| Model Facility Type | Technical Applicability | Market Penetration Rate (2030) | Reduction Efficiency | Technical Effectiveness (2030) |
|---|---|---|---|---|
| **Non-CDM and uncontrolled facility** | 100% | 100% | 95% | **95%** |
| **New uncontrolled facility** | 100% | 100% | 95% | **95%** |
| **Post-CDM facility** | 100% | 100% | 95% | **95%** |

### IV.8.3.3 Estimating Abatement Project Costs and Benefits

Abatement project costs discussed in the previous section were used to calculate the break-even price for implementing the thermal oxidation technology at each facility type (excluding residual emission facilities). Using the engineering cost data discussed earlier, Table 8-6 presents the example break-even prices for each facility type.

**Table 8-6: Example Break-Even Prices for Abatement Measures in HCFC-22 Production**

| Model Facility Type | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Non-CDM and uncontrolled facility** | 5,932,661 | 0.16 | 0.02 | 0.03 | 0.15 |
| **New uncontrolled facility** | 5,932,661 | 0.12 | 0.02 | 0.02 | 0.12 |
| **Post-CDM facility** | 5,932,661 | 0.00 | 0.02 | 0.00 | 0.02 |

### IV.8.3.4 MAC Analysis Results

The global abatement potential for HFC-23 reductions in HCFC-22 production sector is 255 $MtCO_2e$, which is approximately 89% of projected emissions in 2030. Table 8-6 presents the cumulative reductions achieved at selected break-even prices.

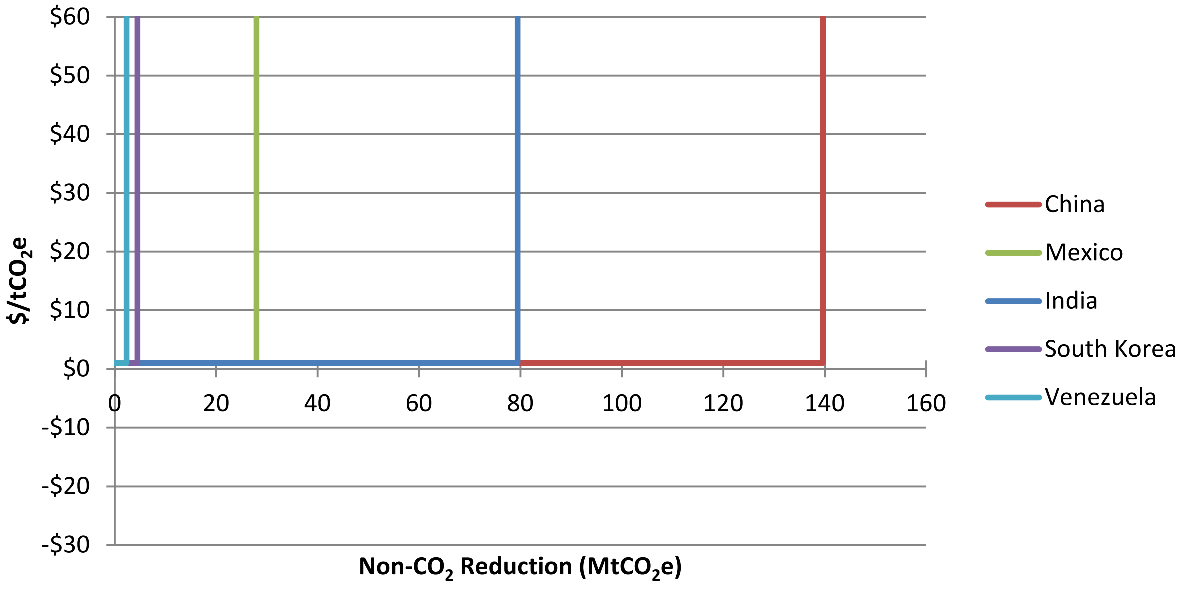
The results are driven largely by the designation of model facilities in different countries. For example, the United States and Russia have zero mitigation potential because they are included in the Annex I group of countries and were assumed to have 100% of their baseline emissions represented by the residual emission model facility (see Table 8-2).

Figure 8-4 shows the corresponding MAC curves for the six countries with abatement potential in 2030, which include China, India, Mexico, South Korea, and Venezuela. Total abatement potential is achieved at break-even prices between $\$0/tCO_2e$ and $\$1/tCO_2e$ in 2030, hence the “L” shape of the curves.

**Table 8-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break Even Price ($/tCO2e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | 10 | 5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | — | — | — | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 | 139.7 |
| India | — | — | — | 79.5 | 79.5 | 79.5 | 79.5 | 79.5 | 79.5 | 79.5 | 79.5 |
| Mexico | — | — | — | 28.0 | 28.0 | 28.0 | 28.0 | 28.0 | 28.0 | 28.0 | 28.0 |
| South Korea | — | — | — | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 |
| Venezuela | — | — | — | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | — | — | — | — | — | — | — | — |
| Central and South America | — | — | — | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Middle East | — | — | — | — | — | — | — | — | — | — | — |
| Europe | — | — | — | — | — | — | — | — | — | — | — |
| Eurasia | — | — | — | — | — | — | — | — | — | — | — |
| Asia | — | — | — | — | — | — | — | — | — | — | — |
| North America | — | — | — | — | — | — | — | — | — | — | — |
| **World Total** | — | — | — | **255.4** | **255.4** | **255.4** | **255.4** | **255.4** | **255.4** | **255.4** | **255.4** |

**Figure 8-4: Marginal Abatement Cost Curves for Countries with Abatement Potential in 2030**



## IV.8.4 Uncertainties and Limitations

This analysis examines a scenario in which the current CDM projects, including those projects with seven-year crediting periods, are completed by 2020.[5] Whether project renewals will occur is uncertain; it is also uncertain whether facilities would continue to abate even in the absence of CDM incentives. Although the first seven-year crediting period for the South Korean plant in Ulsan, which ended in December 2009, was recently renewed for another seven years by the CDM Executive Board in November 2011, the European Commission recommended in January 2011 that the EU cease the purchase of certified emission reductions (CERs) derived from emission mitigation of HFC-23 production after May 2013 (Europa, 2012). In addition to this ban, which has been formally adopted, other countries, such as New Zealand and Australia have announced that they will not accept CERs from HFC-23 destruction projects.

The projections in this analysis are limited to this scenario to examine mitigation costs in the absence of continued CDM projects post-2020; this analysis has not attempted to examine emission projections and MAC curves under a scenario where CDM projects are renewed post-2020.

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

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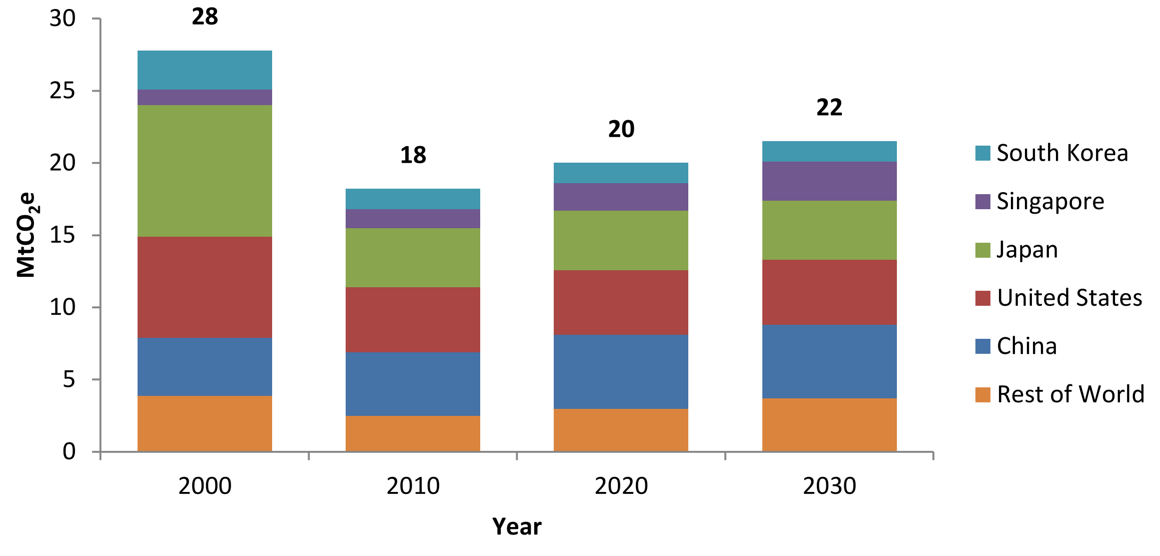
# IV.9. F-GHG Emissions from Semiconductor Manufacturing

## IV.9.1 Sector Summary

The semiconductor manufacturing sector uses several fluorinated greenhouse gases (F-GHGs) including sulfur hexafluoride ($SF_6$), nitrogen trifluoride ($NF_3$), perfluorcarbons (PFCs) such as carbon tetrafluoride ($CF_4$) and perfluoroethane ($C_2F_6$), and the hydrofluorocarbon HFC-23 during fabrication, a portion of which are eventually emitted to the atmosphere. In addition, nitrous oxide ($N_2O$) and several fluorinated heat transfer fluids (HTFs) are used in the sector, but emissions from HTFs and $N_2O$ are not included in this analysis.

Between 2000 and 2010 the production levels in the semiconductor manufacturing industry have rapidly grown, and the complexity of devices produced has advanced substantially. However, over this time period F-GHG emissions from this sector have declined (see Figure 9-1). This reduction can be attributed to ongoing mitigation efforts in response to voluntary emissions reduction goals set by the World Semiconductor Council (WSC). For 2010, the WSC set a quantitative emissions target below the baseline level, and for 2020 it has set an emissions rate target which will entail further implementation of mitigation technologies.[1]

**Figure 9-1: Projected Baseline Emissions from Semiconductor Manufacturing: 2000–2030 ($MtCO_2e$)**



Source: U.S. Environmental Protection Agency (USEPA), 2012

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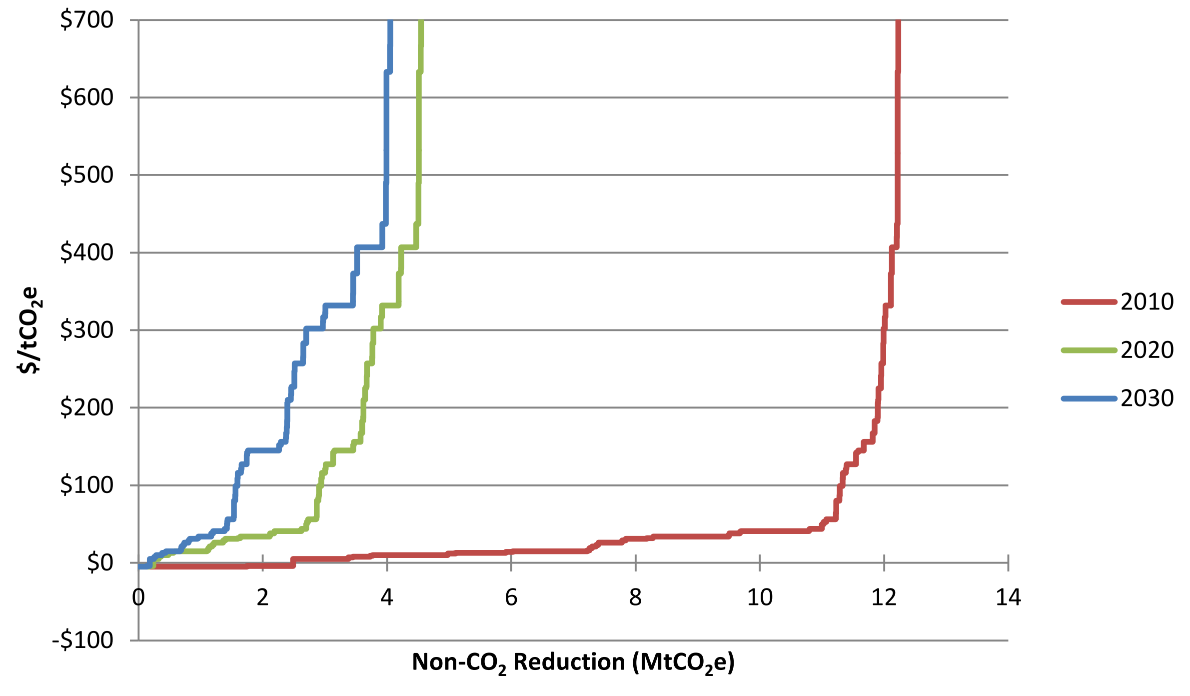
[1] The emissions projection baseline used here is based on the projection presented in USEPA (2012). That analysis was conducted before the details of the 2020 WSC voluntary commitment were available. The projection assumes a continuation of meeting an absolute emissions-level goal through 2030. Further analysis is needed to estimate future emissions as a result of the new normalized emission rate goal set by the WSC, which will depend on future production levels. More information on the specific assumptions in the baseline are available in USEPA ( 2012), and more information on the new WSC goal can be found at http://www.semiconductors.org/news/2013/05/28/news_2013/global_semiconductor_leaders_reach_agreement_on_plan_to_strengthen_industry_through_international_cooperation/

Six mitigation technologies are considered which reduce F-GHG emissions from semiconductor manufacturing: thermal abatement systems, catalytic abatement systems, plasmas abatement systems, the $NF_3$ remote chamber clean process, gas replacement, and process optimization. Significant implementation of these technologies is included in the baseline projection as part of meeting global voluntary targets. The following mitigation analysis is intended to characterize further reductions beyond this level, meaning that reductions are fewer and more costly than reductions would be applied to an uncontrolled baseline.

Mitigation costs and potentials for a particular facility depend on a variety of factors including the processes and gases used, and emissions reduction technologies already in use. The analysis in this chapter considers mitigation technologies applied to two stylized facilities: one representing a "new facility" with relatively new semiconductor technologies and processes and which has already implemented a suite of mitigation technologies, and one "old facility" which has relatively older semiconductor technologies and processes and limited existing use of emissions reduction technologies. Full details on the model facilities are in Section IV.9.4.2.

Global abatement potential of F-GHG emissions in semiconductor manufacturing is estimated to be 12 $MtCO_2e$ in 2010, 4.6 $MtCO_2e$ in 2020 and 4.2 $MtCO_2e$ in 2030. These abatement amounts correspond to 67%, 23%, and 20% respectively in 2010, 2020, and 2030. Figure 9-2 presents the sector marginal abatement cost (MAC) curves for these three years. The relative availability of potential further reductions below the baseline projections declines in later years because more mitigation technology is already included in the baseline as part of meeting voluntary reduction goals. In 2030, less than 1% of the technically feasible reductions could be supplied cost-effectively (at or below a zero break-even price), and nearly 7% of those reductions would be achievable at a carbon price of $50/$tCO_2e$.

**Figure 9-2: Global Abatement Potential in Semiconductor Manufacturing: 2010, 2020, and 2030**



This chapter begins by providing a brief discussion of activities and sources of F-GHG emissions in the semiconductor manufacturing process, and presents the projected emissions from 2010 to 2030. This is followed by an overview of the abatement measures available to the sector for achieving reductions, their technological parameters, and economic costs and benefits. The chapter concludes with a discussion of the MAC analysis and regional MAC results.

## IV.9.2 Emissions from Semiconductor Manufacturing

Semiconductor manufacturing emissions considered in this analysis result from two main types of manufacturing processes used: the etching of substrates and the cleaning of chemical vapor deposition (CVD) chambers. In addition to direct emissions of portions of F-GHGs that are not consumed in these processes, by-product emissions of $CF_4$ and other gases (e.g., $C_2F_6$) occur when a fraction of the gases used in processes react to form other F-GHGs.

Other than etching and chamber cleaning, at least three other semiconductor manufacturing processes result in greenhouse gas emissions. This includes the use of F-GHGs in cleaning wafers, the use of nitrous oxide in chemical vapor deposition and other processes, and the use of fluorinated heat transfer fluids. However, these emitting processes were not considered in this analysis because there is very limited public information that would make estimating emissions from them feasible. In the future, if more quantitative information is gathered on these three emissive uses of F-GHGs, they can be considered in an updated analysis.

For the purpose of evaluating the cost of reducing F-GHG emissions from semiconductor manufacturing, this analysis considers the apparent differences in emissions resulting from newer and older manufacturing processes and mitigation practices; reduction costs for two typical fabrication facilities (fabs), which were generally characterized based on fab capacity (i.e., the number of manufacturing tools a typical fab may have); and the existing use of various mitigation technologies to etch and clean emissions. The emissions breakdown illustrated in Figure 9-3 represent emissions from these two types of fabs, further broken out by emission from etch and chamber clean processes. In 2020, new facilities are expected to make up 30% of global emissions, with old facilities accounting for the remainder. A description of the characteristics of the old and new fab considered for purposes of analysis is contained in Section IV.9.4.2.

### IV.9.2.1 Activity Data or Important Sectoral or Regional Trends

Several important industry trends drive changes in emissions and mitigation potential from semiconductor manufacturing: 1) rapid production growth, 2) evolving manufacturing processes and increasing complexity in devices produced, and 3) impacts of mitigation efforts resulting from voluntary emissions reduction goals. These trends are described below.

Between 2001 and 2011, global semiconductor manufacturing, measured on the basis of total manufactured layer area (TMLA), indicates a compound annual growth rate of approximately 10% per year, which is higher than the silicon consumption growth rate of approximately 7% per year (VLSI, 2012 and WFF, 2012).[2] Both silicon area and TMLA are metrics of semiconductor production; however the difference in growth rate is driven by the increasing complexity of devices, as TMLA reflects

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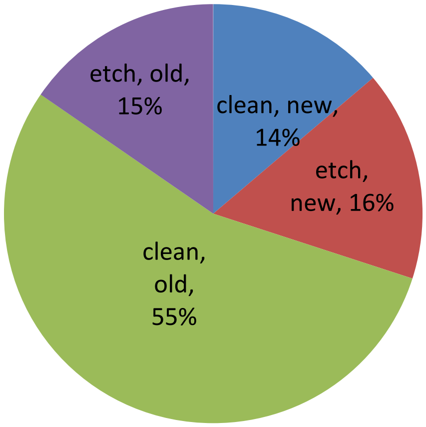
[2] Silicon consumption was taken from VLSI, 2012. TMLA was derived in the EPA PFC Emissions Vintaging Model using data from VLSI, 2012 and WFF, 2012.

**Figure 9-3: Global F-GHG Emissions in 2020 by Fab Type and Process (% of GWP-Weighted Emissions)**



the silicon wafer base layer plus all the metal interconnect layers and the silicon consumption reflects just the base. More recently production growth has slowed. Between 2006 and 2011, annual production growth is estimated to be about 5% on a TMLA basis, or 4% on a silicon area basis.

Etch and chamber-cleaning processes have evolved as semiconductor technologies have advanced and understanding of the emission pathways associated with manufacturing has improved. As technologies advanced, the semiconductor industry used larger wafer sizes to increase to increase chip production (e.g., 150 mm to 200 mm to 300 mm). Fabs that produce semiconductors on smaller wafers, on average, tend to be older and use manufacturing processes that result in a different breakdown of F-GHG emissions from etch and clean processes as compared to newer fabs. Older fabs may emit approximately 80% of F-GHG emissions total from chamber-cleaning processes and about 20% of emissions from etch processes. These percentages change to about 45%/55% clean/etch for newer fabs. This shift in the source of emissions over time is a result of the following: 1) newer fabs generally are trending to $NF_3$ remote-clean technologies that result in lower emissions on a $CO_2$e basis than traditional older $C_2F_6$- or $C_4F_8$-based clean systems, 2) more technologically advanced etch processes have a significantly greater number of steps, resulting in more F-GHG emissions, and 3) newer fabs can have less physical limitations on using abatement. As a new generation of fabs come online using 450 mm wafers, it is expected they will continue to use $NF_3$ remote clean technologies, abatement, and more advanced etch processes.

The WSC set an absolute emissions reduction goal for 2010 and a further emissions rate reduction goal for 2020. The 2010 WSC goal was an emission reduction of 10% relative to 1995 baseline F-GHG emissions.[3] This emission reduction goal was met in 2010. Achievement of the 2010 WSC emissions reduction goal has occurred in the context of significantly increasing underlying manufacturing activity. A 2011 joint WSC statement reported that the participating industry associations had achieved a collective 32% reduction from their baselines while semiconductor industry production increased roughly six times over the same time period (WSC, 2011).

In 2011, the WSC outlined a new voluntary F-GHG agreement for 2020 (WSC, 2011). This agreement sets a normalized emission rate goal of 0.22 $kgCO_2e/cm^2$, which is a 30% reduction from the 2010 WSC aggregate baseline emissions rate (including China, which was not included in the 2010 goal) of 0.33

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[3] Korea has a baseline year of 1998.

kgCO$_2$e/cm$^2$. In the 2020 voluntary goal the WSC also strongly suggests the use of best practices at newly built manufacturing facilities.[4] EPA has not yet analyzed how this new agreement would relate to absolute emission reductions in WSC countries, however achieving this goal would require significant use of mitigation technologies. The baseline used for this analysis assumes continued production growth and continued implementation of mitigation technologies; however it was estimated before the details of the 2020 WSC goal were available. Further analysis is necessary to estimate expected semiconductor manufacturing emission accounting for the 2020 WSC goal. Incorporating the new goal would likely result in somewhat reduced projected emissions in 2020 and somewhat increased projected emissions for 2030.

### IV.9.2.2 Emissions Estimates and Related Assumptions

Projected emissions are based on estimated production level and capacity (described above), emissions rates drawn from voluntary reporting in the U.S., emissions as reported to the UNFCCC, and achievement of voluntary goal levels.

The preferred activity data to determine semiconductor emission estimates are gas consumption data. However, this information is not available globally. Instead, limited data on gas usage from the USEPA Voluntary Semiconductor Partnership was used to calculate emissions in relation to production. Therefore, emissions were estimated using this information, emission estimates from the UNFCCC, and alternative activity data, which is production capacity.

As described above, this analysis takes into account voluntary mitigation activities in the various WSC member countries and assumes that member countries maintain emissions at the goal level in the future. Projected emissions for major countries and regions are presented in Table 9-1.

**Table 9-1: Projected Baseline Emissions from Semiconductor Manufacturing: 2010-2030 (MtCO$_2$e)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010 2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| United States | 4.4 | 6.3 | 5.1 | 5.1 | 5.1 | 0.7% |
| China | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 0.0% |
| Japan | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 0.0% |
| Singapore | 1.3 | 1.6 | 1.9 | 2.3 | 2.7 | 3.9% |
| South Korea | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 0.0% |
| **Rest of Regions** | | | | | | |
| Africa | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 5.0% |
| Central and South America | — | — | — | — | — | — |
| Middle East | 0.2 | 0.3 | 0.3 | 0.4 | 0.5 | 4.3% |
| Europe | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 0.0% |
| Eurasia | 0.1 | 0.2 | 0.2 | 0.3 | 0.4 | 4.6% |
| Asia | 0.4 | 0.5 | 0.6 | 0.8 | 1.0 | 5.4% |
| North America | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 3.0% |
| **World Total** | **18.2** | **20.6** | **20.0** | **20.7** | **21.5** | **0.8%** |

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

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[4] Best practices, which will be continuously reviewed and updated by the WSC, can be found here: http://www.semiconductorcouncil.org/wsc/uploads/Final_WSC_Best_Practice_Guidance_26_Sept_201-2.pdf

To estimate potential for further reductions beyond the voluntary control levels included in the baseline emissions projection, emissions must be allocated between uncontrolled emissions and residual emissions remaining after control measures have been implemented. Specific information on current use of mitigation technologies is not available, so the degree of mitigation is inferred by considering two stylized model facilities: one where almost full mitigation is used and one where almost no mitigation is used, and from comparing emission rates for controlled and uncontrolled facilities as determined using data reported through EPA's Greenhouse Gas Reporting Program (USEPA, 2013) and information gathered during EPA's voluntary partnership with the semiconductor industry.

## IV.9.3 Abatement Measures and Engineering Cost Analysis

Six mitigation technology options were considered for the semiconductor manufacturing sector: thermal abatement, catalytic abatement, plasma abatement, $NF_3$ remote chamber clean, gas replacement, and process optimization.

- **Thermal abatement**: These point-of-use abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through abatement systems with catalysts (e.g., CuO, ZnO, $Al_2O_3$) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma, in a point-of-use abatement system, is used to react with (thereby destroying or removing) F-GHGs from the process effluent stream.
- **$NF_3$ remote chamber clean**: Highly ionized $NF_3$ is used to clean chemical vapor deposition chambers. This process is very efficient (using ~98% of the gas in a process) resulting in lower emissions on a mass and $CO_2$ basis than traditional in-situ chamber clean processes that use approximately 20% to 50% of the gas in a process and have lower efficiencies (USEPA, 2010).
- **Gas replacement**: Higher global warming potential (GWP) gases are replaced with lower GWP gases, and in some cases more efficient gases (e.g., $C_4F_8$ may replace $C_2F_6$ in a traditional chamber-cleaning process).
- **Process optimization**: Processes are adjusted to become more efficient, using more gas within the process, and thus resulting in lower emissions.

These technologies reduce emissions from either etch or chamber-cleaning processes or in some cases both. Table 9-2 demonstrates the applicability of each mitigation technology to each process type. While in reality some of these technologies can be stacked, or used together (e.g., a process can be optimized and then abatement can be applied to that process), the cost and mitigation analysis does not model this situation.

**Table 9-2: Semiconductor Manufacturing Abatement Options**

| Fab/Emissions Type | Thermal Abatement | Catalytic Abatement | Plasma Abatement | NF3 Remote Clean | Gas Replacement | Process Optimization |
|---|---|---|---|---|---|---|
| **Reduction Efficiency** | **95%** | **99%** | **97%** | **95%** | **77%** | **54%** |
| **New fab** | | | | | | |
| Etch emissions | X | X | X | | | |
| Clean emissions | X | | | X | | |
| **Old fab** | | | | | | |
| Etch emissions | X | X | X | | | |
| Clean emissions | X | | | X | X | X |

Table 9-3 presents a summary of the engineering cost data for each of the mitigation technologies.

**Table 9-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Project Lifetime (years) | | Capital Costs (2010 USD) | | Annual Costs (2010 USD) | | Abatement Amount ($tCO_2e$) | |
|---|---|---|---|---|---|---|---|---|
| | New | Old | New | Old | New | Old | New | Old |
| Thermal abatement | 7 | 7 | $11,403,942 | $5,701,971 | $657,723 | $328,862 | 10,497 | 52,375 |
| Catalytic abatement | 7 | 7 | $13,813,189 | $6,906,594 | $910,555 | $455,277 | n/a | 11,851 |
| Plasma abatement | 7 | 7 | $3,629,329 | $1,814,664 | $103,695 | $51,848 | n/a | 11,612 |
| $NF_3$ remote clean | 22 | 11 | $3,005,084 | $9,200,867 | $1,214,892 | $3,374,861 | 1,166 | 41,002 |
| Gas replacement | 22 | 11 | n/a | $1,180,000 | n/a | $64,231 | n/a | 29,911 |
| Process optimization* | 22 | 11 | n/a | $109,440 | n/a | ($129,071) | n/a | 20,976 |

Note: Values in parentheses denote negative costs.

*Values listed as capital costs for process optimization represent one-time labor costs, not cost of capital.

### IV.9.3.1 Thermal Abatement

Thermal abatement systems can be used to abate emissions from both etching and CVD chamber-cleaning processes by heating process effluent streams to high temperatures to remove or destroy F-GHGs. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in sub-fabs, particularly in older facilities. In addition, these systems require large amounts of cooling water, and the system's use results in regulated $NO_x$ emissions. Thermal abatement systems are currently the most widely used abatement system in the semiconductor industry.

The engineering cost estimates for this technology are as follows:

- **Capital Costs:** Thermal abatement system capital costs cover the cost of the abatement unit with ducting and water recirculation ($157,000 per unit), hook-up costs ($35,550), and natural gas infrastructure costs ($35,550) (Fthenakis, 2001; Burton, 2003). One unit is needed per tool at a facility. The total facility capital cost ranges from $11.4 million for new fabs to $5.7 million for old fabs.
- **Annual Costs:** Annual operating costs per manufacturing tool, as presented in Table 9-4, are the same for both new and old fabs. Total annual costs (e.g., utilities) for a new fab are estimated to be $658,000 and $329,000 for an old fab. The higher capital and annual costs for new fabs are based on the fact that new fabs typically have larger manufacturing capacities (i.e., more tools) (WFF, 2011). Annual costs per tool are summarized in Table 9-4. The per-tool cost is the same for both new and old fabs.
- **Annual Revenue**: No financial benefits (e.g., cost savings) are associated with using this mitigation technology without outside policy or other drivers.
- **Reduction Efficiency:** This analysis assumes a 95% reduction efficiency (Fthenakis, 2001; Beu, 2005; USEPA, 2009).
- **Technical Lifetime:** Based on expert judgment, it was estimated that the average lifetime of this system, and other abatement systems discussed in this analysis, is 7 years.

**Table 9-4: Annual Cost per Tool for Thermal Abatement Systems**

| Annual Cost Component | Cost (2010 USD) |
|---|---|
| Water/waste water/maintenance | **$2,370** |
| Consumables | **$5,330** |
| Electricity | **$2,610** |
| **Natural gas** | **$2,840** |

Source: Burton, 2003.

### IV.9.3.2 Catalytic Abatement

A catalytic abatement system uses a catalyst to destroy or remove F-GHG emissions from the effluents of both plasma etching and CVD chamber-cleaning processes. This type of abatement is applicable at most facilities, but there may be some space constraints as mentioned above for thermal abatement systems. Additionally, because these systems are based on destruction via catalyst, they must be process/stream specific to achieve the 99% emission reductions quoted in the literature and used in this analysis (Fthenakis, 2001; Burton, 2003).

Because catalytic destruction systems operate at relatively low temperatures, their use results in little or no $NO_x$ emissions, and the required amounts of water are also low. Because of the high cost of catalyst replacement, these systems are the least widely used type of abatement (expert judgment).

Cost estimates for this technology are as follows:

- **Capital Costs.** Capital costs are associated with purchasing and installing the abatement systems (Burton, 2003). One unit costs $217,010, and the installation costs $59,250, leading to estimated costs of $6.9 million and $13.8 million for old and new fabs, respectively.
- **Annual Costs.** Facilities incur annual costs per tool for water ($3,790), waste chemicals ($60), catalyst replacement ($12,580), and electricity ($1,780) (Burton, 2003). A new fab incurs annual costs for catalytic abatement of $910,600, and an old fab incurs costs of $455,300.
- **Annual Revenue.** No cost savings are associated with this technology.
- **Reduction Efficiency:** The analysis assumes 99% reduction efficiency for catalytic abatement (Fthenakis, 2001).
- **Technical Lifetime:** Seven years.

### IV.9.3.3 Plasma Abatement

These systems, which use plasma to remove or destroy F-GHGs, are applicable to etch processes in most facilities, with some physical space limitations. (These systems, though, are smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen ($H_2$), oxygen ($O_2$), water ($H_2O$), or methane ($CH_4$) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no GWP. After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of F-GHG molecules (Motorola, 1998).

A plasma abatement system is needed on each tool chamber. The costs of plasma abatement systems are developed using the following information:

- **Capital Costs:** The plasma abatement technology requires capital costs that cover the purchase and installation of the system, which total $41,500 per chamber, equating to one-time costs of $3.6 million for new fabs and $1.8 million for old fabs (Fthenakis, 2001; Burton, 2003).
- **Annual Costs:** Facilities with plasma abatement systems are estimated to incur annual operation costs of $1,190 per chamber, which includes general maintenance and use of the system. Total annual facility costs are $103,700 for new fabs and $51,800 for old fabs, based on the assumption that there are 3.5 chambers per etch tool and varying numbers of tools for new and old fabs (Fthenakis, 2001; Burton, 2003).
- **Annual Revenue:** As with other abatement technologies, the use of plasma abatement systems will not result in any cost savings.
- **Reduction Efficiency:** The emissions reduction efficiency of this option is estimated to be 97% (Fthenakis, 2001; Hattori et al., 2006).
- **Technical Lifetime:** 7 years.

### IV.9.3.4 $NF_3$ Remote Chamber Clean

$NF_3$ remote chamber clean is an alternative cleaning technology that offers the benefit of having a particularly high (~98%) utilization rate of $NF_3$ (IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. $NF_3$ remote clean systems dissociate $NF_3$ using argon gas, and converting the source gas to active F-atoms in the plasma upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine ($F_2$), and other gases, most of which are removed by facility acid scrubber systems. The use of $NF_3$ remote clean systems is much more prevalent in newer fabs because the technology was not available when many older fabs were constructed.

Capital costs for $NF_3$ remote clean systems will differ for new and old fabs because of the "readiness" for $NF_3$ remote clean installation. "Readiness" consists of having the current infrastructure (e.g., duct work, hook-ups) for system installation. It was assumed that old fabs are do not have the current infrastructure to use NF3 remote clean, whereas new fabs do. Therefore, the capital costs for old fabs reflect the needed infrastructure changes for the fab.

Cost assumptions include the following:

- **Capital Costs:** Both facility types would incur capital costs for purchasing the $NF_3$ remote system and the additional necessary $F_2$ scrub for use after the chamber cleaning of the waste stream. The costs for system purchase for a new fab are estimated to be $3 million. Old fabs are assumed to not be "$NF_3$ ready," or in other words, these facilities are not assumed to have the current infrastructure to handle the direct installation of $NF_3$ remote systems. Therefore, old fabs also incur capital costs, in addition to system costs, associated with investments such as gas hook-ups and necessary hardware such as manifolds and valves in addition to the costs of the systems which are assumed to be already installed at new fabs. (These costs are detailed in Table 9-5.) The old fab costs are estimated to be $9.2 million.
- **Annual Costs:** Facilities operating $NF_3$ remote clean systems are subject to annual costs that include the purchase of larger volumes of gas ($NF_3$ versus traditional chamber-cleaning gases such as $C_2F_6$), general maintenance, and the cost of $F_2$ scrubs to remove the highly explosive gas from the effluent. Remote clean requires a lot of $NF_3$, so much so that $NF_3$ purchases are estimated to comprise anywhere from 25% to upward of 75% of annual facility gas consumption (expert judgment). New fab costs annually for $NF_3$ remote clean are estimated to be $1.2 million and to be $3.4 million for old fabs (Burton, 2003).

Table 9-5: Capital Costs per CVD Chamber for Making a Facility $NF_3$ Ready

| Activity | Capital Cost (2010 USD) |
|---|---|
| Labor/gas hookup | **$3,980** |
| $NF_3$ manifold, valves, etc. | **$16,591** |
| Toxic monitor | **$7,700** |
| **Stainless steel line (double walled)** | **$10,310** |

Source: Burton, 2003

- **Annual Revenue:** No cost savings are assumed to be associated with this technology.
- **Reduction Efficiency:** The analysis assumes this technology offers a reduction of 95% of emissions (Beu, 2005).
- **Technical Lifetime:** Once the remote clean systems are installed, they will last for the lifetime of a facility. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab and 22 years for a new fab.

### IV.9.3.5 Gas Replacement

Gas replacement can be used to mitigate emissions from the traditional CVD chamber-cleaning process. This method can be applied in most facilities and has already been used throughout the industry in many instances. For this strategy, a lower GWP gas replaces a higher GWP gas. The most common replacement seen is using $C_4F_8$ to replace $C_3F_8$ or $C_2F_6$. In addition, the replacement gas ($C_4F_8$ ) is often used/consumed more efficiently during CVD chamber cleaning than the original gas $C_2F_6$ or $C_3F_8$, which, combined with the differences in GWP, yields lower emissions.

As with most other technologies considered in this analysis, there are no associated cost savings.

- **Capital Costs.** Facilities replacing $C_2F_6$ or $C_3F_8$ with $C_4F_8$ face a capital expenditure that reflects the aggregate cost of the $C_4F_8$ gas hook-up and an engineer's time cost for implementation. Based on the Clean Development Mechanism (CDM) number NM0317, the aggregated cost of equipment, $C_4F_8$ gas hook-up, and an engineer's time for implementation and installation is estimated to be $1.2 million for old fabs (the technology is not assumed to be used at new fabs).
- **Annual Costs.** Facilities face an annual cost that reflects the cost of replacing $C_2F_6$ or $C_3F_8$ with the more expensive $C_4F_8$. The costs of these gases, taken from CDM NM0303, are $35 per kilogram of $C_2F_6$, $26 per kilogram of $C_3F_8$, and $72 per kilogram of $C_4F_8$. Costs for old fabs were estimated to be $64,230, which is based on an average amount of gas consumed per facility. Gas consumption information was estimated based on USEPA Voluntary Partnership data, in which facility age and gas consumption relationships were not distinguishable.
- **Annual Revenue.** No cost savings are associated with this technology.
- **Reduction Efficiency:** The analysis assumes a reduction efficiency of 77% for this mitigation technology (CDM methods NM0289, NM303, NM0317, NM0335).
- **Technical Lifetime:** As with $NF_3$ remote clean, once a gas is replaced, the "new" process will last for the lifetime of a fab. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab.

### IV.9.3.6 Process Optimization

Process optimization is the reduction in GHG emissions from a process by modifying or adding to the process recipe. Process optimization is considered to be only applicable for chamber cleans because these processes offer the opportunity for more flexibility than etch processes. Etch processes are typically developed to optimize production yield, and they are only adjusted to increase this yield; a company would not risk negatively impacting it (Beu, 2005; Fthenakis, 2001). Process gas optimizations for CVD clean processes can be implemented because adjustments to these processes are much less precise than etch processes. There is room to reduce emissions without affecting yield. Optimization of clean processes to reduce emissions usually results in small production gains but sometimes can result in large increases in efficiency.

Facilities optimizing processes incur labor costs of an estimated $109,440; it is assumed that old fabs incur this cost, while new fabs do not implement this technology due to their assumed use of NF3 remote clean for the majority of clean processes.

Details of the cost estimates for this technology include the following:

- **One Time Labor Costs:** Facilities' optimizing processes incur a one-time labor cost. Labor costs of $43 per hour were used for a materials engineer in the semiconductor industry based on BLS (2010) information and an estimated 2,560 hours of work, resulting in a total labor cost for each model facility of $109,440.
- **Annual Costs:** No annual costs are associated with process optimization for clean processes that are outside of business-as-usual (BAU) annual facility costs.
- **Annual Revenue:** Because process optimization involves adjusting a process to perform more efficiently, the cost savings associated with this option are due to a lowered amount of gas required to be purchased. For simplicity, the process considered in this analysis for this option was a $C_2F_6$ traditional chamber clean, and the related savings were estimated to be $129,070. As for the gas replacement annual cost, this number varies depending on the size of the facility. However, consumption information was only able to be estimated based on USEPA Voluntary Partnership data, in which facility age and gas consumption relationships were not distinguishable.
- **Reduction Efficiency:** Observed reduction efficiencies for abatement of $C_2F_6$ in the literature range from 10% to 56% (Beu, 2005) and as high as 75% (Fthenakis, 2001). For the purposes of this analysis, an average reduction efficiency of 54% was used, and we assumed the change in process is permanent over the life of a facility.
- **Technical Lifetime:** As with $NF_3$ remote clean, once a gas is replaced, the "new" process will last for the lifetime of a fab. Based on information from the World Fab Forecast, the average remaining lifetime of a facility is 11 years for an old fab.

## IV.9.4 Marginal Abatement Cost Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for semiconductor manufacturing.

### IV.9.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at two hypothetical facilities to calculate a break-even price for each option at each facility (new and old). This section presents detailed information on how each type of fab was defined in this analysis, and detailed information on how costs were built out for each mitigation technology.

### IV.9.4.2 Definition of Model Facilities

For this sector, two fab types were considered: an old fab and a new fab. The differences between these two fabs are discussed in more detail below:

- **Old:** The old fab is intended to capture facilities that use smaller wafer sizes, such as 150 mm and below, as well as some older 200 mm manufacturing facilities (i.e., fabs built before 2000). This fab is expected to use less current manufacturing processes and produce less, in terms of silicon area. was estimated for this analysis, based emissions data reported through the U.S. EPA Greenhouse Gas Reporting Program, that a typical "old" fab breakdown of emissions on a $CO_2e$ basis is approximately 20% etch emissions and 80% clean emissions. This is because older etch processes involve less GHG-using steps and more commonly use traditional chamber cleans with gases such as $C_2F_6$ as opposed to remote chamber cleaning processes. This fab is also expected to not use any abatement and only use minimal process optimization and gas switching. It was assumed that an old fab has an average of 30 tools with 3.5 chambers per tool.[5]
- **New:** The new fab type encompasses facilities that use larger wafer, such as 300 mm wafers. It is estimated, based again on emissions data reported through the U.S. EPA Greenhouse Gas Reporting Program, that the total emission breakdown for the new fab is approximately 55% etch emissions and 45% clean emissions. In contrast to the old fab, the new fab uses more recent etch processes that have comparatively many more GHG-using steps and the fab has higher production, in terms of silicon area.[6] Another process shift seen in newer fabs is the trend toward using $NF_3$ remote chamber cleans as opposed to traditional chamber cleans, which results in relatively lower cleaning emissions. New fabs are assumed to use $NF_3$ remote clean mainly, and have abatement on all etch processes and all in situ chamber cleaning processes. It was assumed that new fab facility has about 50 tools with 3.5 chambers per tool.

The emission breakdowns are essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process. One other important factor is facility size. Newer fabs tend to have relatively larger production capacities than older fabs, and this difference was taken into account in this analysis.

The facilities used represent two clearly defined and distinct types of facilities. These defined facilities represent two existing scenarios, a better existing mitigation case and a worse existing mitigation case, for semiconductor manufacturing fabs. Given the variety of mitigation options, there are facilities that exist that may be in the somewhere between the two scenarios modeled. For instance, some fabs may partially abate emissions as opposed to using full abatement or no abatement. These fabs were not explicitly considered in this analysis due to the uncertainty associated with developing assumptions about their current mitigation practices.

### IV.9.4.3 Assessment of Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process/facility type combination. Estimating this parameter requires making a number of assumptions regarding the distribution of emissions by manufacturing process (etch and clean) in addition to process-specific estimates of technical applicability and market penetration. The

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[5] CVD and etch tools generally vary between having three to four chambers.

[6] Although newer etch processes are more efficient (i.e., gas utilization is higher) than older processes, the relative number of GHG-using steps in more recent processes negates the potential benefit of higher utilization of gas when considering overall facility etch emissions.

split of etch to clean emissions is held constant for all years. The technical applicability and market penetration of mitigation technologies is held constant over time for new facilities as it is assumed these facilities are addressing emissions as much as possible already. Whereas, technical applicability and market penetration for old facilities varies over time as it is assumed that more action will need to be taken by older facilities to meet stated voluntary reduction goals. Table 9-6 presents the assumed distribution of annual facility-level emissions by process for each fab type.

**Table 9-6: Percentage of Annual Emissions by Process and Fab Type**

| | Percentage of Total Annual Emissions | |
|---|---|---|
| Process | **New** | Old |
| Etch | 54% | **22%** |
| Clean | 46% | **78%** |
| **Total** | **100%** | **100%** |

Table 9-7 and Table 9-8 report the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness at new and old fabs. The technical effectiveness is the weighted average of the abatement measures using the process emissions presented in Table 9-6 for each process as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency.

**Table 9-7: Technical Effectiveness Summary for New Fabs (Constant Over Time)**

| | Etch (54%) | | Clean (46%) | | | |
|---|---|---|---|---|---|---|
| Abatement Measure | Technical Applicability | Market Penetration | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
| Thermal abatement | 0% | 0% | 90% | 50% | 95% | **20%** |
| Catalytic abatement | 0% | 0% | 0% | 0% | 99% | **0%** |
| Plasma abatement | 0% | 0% | 0% | 0% | 97% | **0%** |
| $NF_3$ remote clean | 0% | 0% | 10% | 50% | 95% | **2%** |
| Gas replacement | 0% | 0% | 0% | 0% | 77% | **0%** |
| Process optimization | 0% | 0% | 0% | 0% | 54% | **0%** |

**Table 9-8: Technical Effectiveness Summary for Old Fabs (in 2020)**

| | Etch (20%) | | Clean (80%) | | | |
|---|---|---|---|---|---|---|
| Abatement Measure | Technical Applicability | Market Penetration | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
| Thermal abatement | 50% | 90% | 50% | 15% | 95% | **15%** |
| Catalytic abatement | 50% | 5% | 0% | 5% | 99% | **1%** |
| Plasma abatement | 50% | 5% | 0% | 0% | 97% | **1%** |
| $NF_3$ remote clean | 0% | 0% | 100% | 5% | 95% | **4%** |
| Gas replacement | 0% | 0% | 10% | 40% | 77% | **2%** |
| Process optimization | 0% | 0% | 10% | 40% | 54% | **2%** |

Technical applicability assumptions presented in Table 9-7 and Table 9-8 are intended to reflect the space limitations or preexisting process performance issues that are likely to be found at a fraction of all facilities, particularly old facilities, preventing the total implementation of the abatement measures. Assumed market penetration rates are based on cost (lower cost options will penetrate the market more) and expert knowledge of industry trends. For example, fabs tend to use thermal abatement more than the other technologies in their etching processes. In addition, it was assumed that because most new fabs already have $NF_3$ remote systems in place less market share would go to gas replacement and process optimization.

The technical effectiveness estimates are then multiplied by the share of total emissions for each facility type to estimate the abatement potential achievable under each abatement measure. For the purposes of this analysis we assume a 10/90 split in 2010 for the distribution of annual emissions coming from new and old fabs. In future years, we assume based on expert judgment the share of total emissions coming from new fabs increases by 10% each year to account for the use of best practices by WSC members, old fabs closing and changes in wafer size/technology demands.

### IV.9.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.9.3 to calculate the break-even price for each mitigation option at both new and old fab facilities. Table 9-9 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Although new fabs have lower break-even prices for thermal, catalytic, and plasma abatement measures, old fabs have lower break-even prices for $NF_3$ remote clean, gas replacement, and process optimization because of their relatively smaller size. Note that process optimization is the only negative break-even price option because of its low one-time cost and relatively high annual cost savings.

**Table 9-9: Example Break-Even Prices for Abatement Measures in Semiconductor Manufacturing**

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price[a] ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **New fabs** | | | | | |
| Thermal abatement | 41,199 | 85 | 14 | 24 | **76** |
| Catalytic abatement | 8,096 | 526 | 101 | 146 | **481** |
| Plasma abatement | 11,833 | 94 | 8 | 26 | **76** |
| $NF_3$ remote clean | 22,551 | 114 | 242 | 18 | **338** |
| Gas replacement | 6,240 | 36 | 10 | 6 | **40** |
| Process Optimization | 1,648 | 13 | −78 | 2 | **−68** |
| **Old fabs** | | | | | |
| Thermal abatement | 22,802 | 103 | 17 | 29 | **91** |
| Catalytic abatement | 4,575 | 620 | 119 | 173 | **567** |
| Plasma abatement | 3,293 | 226 | 19 | 63 | **182** |
| NF3 remote clean | 37,768 | 75 | 107 | 18 | **165** |
| Gas replacement | 9,753 | 31 | 7 | 7 | **30** |
| Process optimization | 3,864 | 7 | −33 | 2 | **−28** |

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

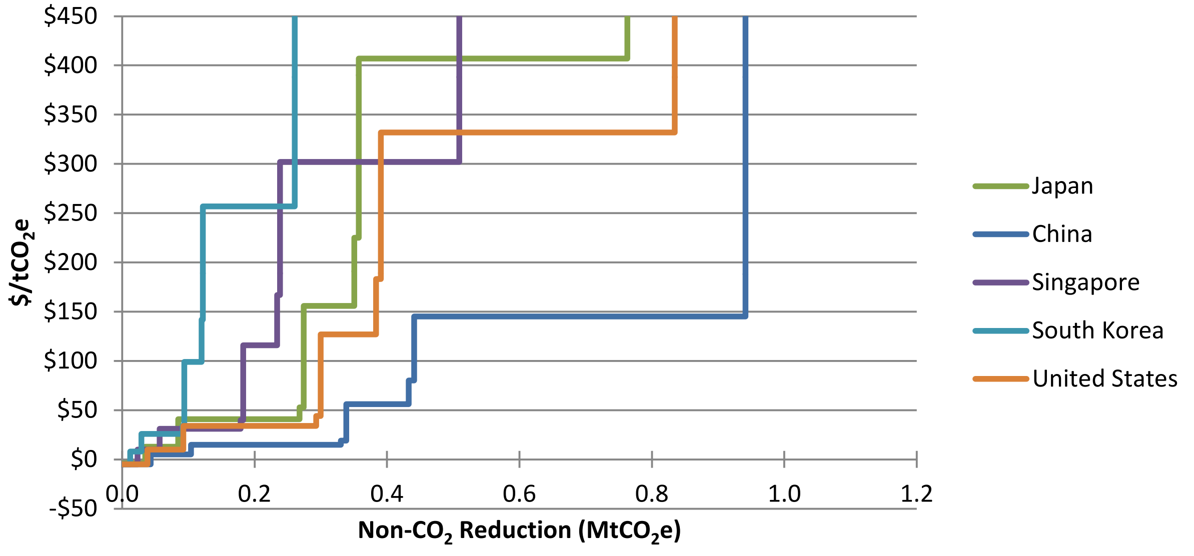
### IV.9.4.5 MAC Analysis Results

The global abatement potential for F-GHG reduction in the semiconductor manufacturing sector is estimated to be 87% of total projected emissions in 2030. Table 9-10 presents the cumulative reductions achieved at selected break-even prices. Figure 9-4 shows the MAC curve for the top five emitting countries for this sector.

**Table 9-10: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break Even Price ($/tCO$_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | 10 | 5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | — | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 1.0 |
| Japan | — | — | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.3 | 0.3 | 0.8 |
| Singapore | — | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.5 |
| South Korea | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.3 |
| United States | — | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0.3 | 0.9 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Central and South America | — | | | | | | | | | | |
| Middle East | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Europe | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 |
| Eurasia | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Asia | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 |
| North America | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **World Total** | **—** | **0.1** | **0.2** | **0.2** | **0.4** | **0.7** | **0.7** | **0.8** | **1.4** | **1.6** | **4.2** |

**Figure 9-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030**



As stated earlier, early voluntary action by the semiconductor manufacturing industry resulted in a dramatic decrease in the level of F-GHG emissions emitted in 2010 and later years as compared with 2000. However, emissions are expected to grow from the current level based on increased demand for semiconductors over the next 20 years, and this may be particularly true in light of the new WSC normalized emission rate goal The MAC analysis suggests that additional reductions from this sector are costly. In the absence of any external climate policy drivers, major reductions in the semiconductor manufacturing sector would require a significantly high carbon price (>$100/tCO$_2$e) to incentivize manufacturers to adopt additional mitigation options.

## IV.9.5 Uncertainties and Limitations

A few key uncertainties exist with respect to the analysis for the semiconductor sector. The extent of current abatement is unclear; there is no comprehensive published information on the extent abatement systems are really in use in the industry. In addition, abatement system reduction efficiencies assumed in this analysis are really only achievable if the systems are properly operated and maintained, which may not always be the case. Also, abatement system reduction efficiencies may vary by gas (e.g., $CF_4$ is harder to abate than other F-GHGs because of its relatively high thermo-stability, or bond strengths). Finally, the pace at which the semiconductor manufacturing sector has advanced has been historically very fast-paced. This continues to be true, but it cannot be certain that this will continue to be true given the continued rising costs of advancement.

The limitations to this analysis are that it could not consider the full picture of emissions from semiconductor manufacturing (e.g., heat transfer fluid emissions are not included), and that the new WSC normalized emission rate goal was not known at the time of the analysis.

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- NM0289: PFC gas emission reduction by gas replacement for CVD cleaning at 200 mm (8 inches) process by Hynix Semiconductor Inc. (submitted September 2008)
- NM0303: PFC gas emissions reduction by gas replacement for CVD cleaning processes in semiconductor processing operations (submitted April 2009)
- NM0317: Substitution of fluorinated compound (FC) gases for cleaning CVD reactors in the semiconductor industry (submitted June 2009)
- NM0330: Substitution of fluorinated compound (FC) gases for cleaning CVD reactors in the semiconductor industry (submitted December 2009)
- NM0332: PFCs emission reduction from installation of an abatement device in a semiconductor manufacturing facility (submitted January 2010)
- NM0335: PFC emission reduction by gas replacement in the process of CVD cleaning in semiconductor production (submitted February 2010)

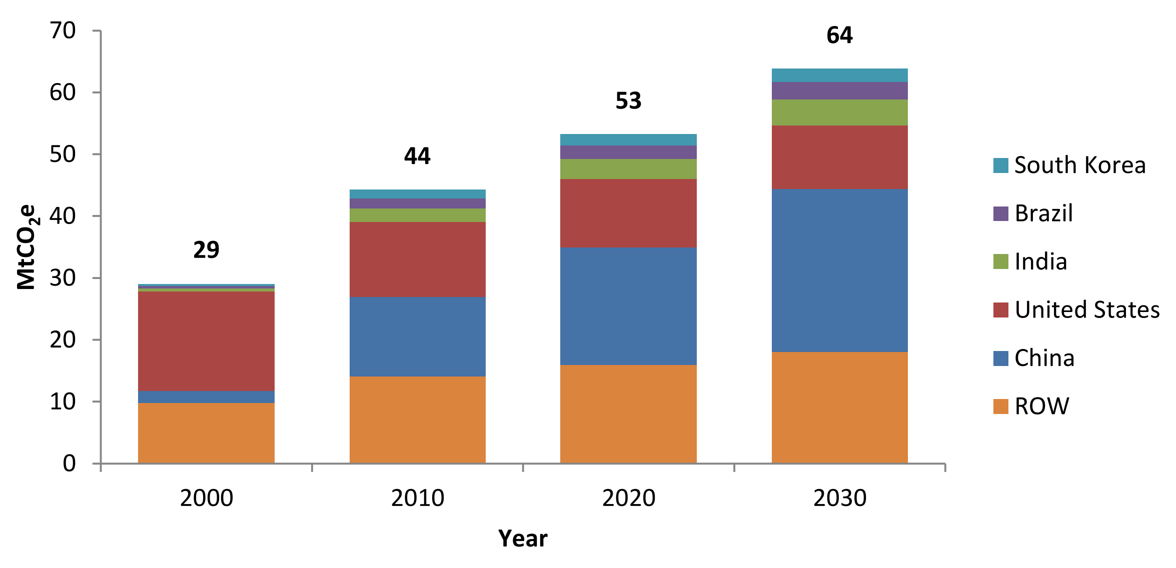
# IV.10. $SF_6$ Emissions from Electric Power Systems

## IV.10.1 Sector Summary

Electric utilities use transmission and distribution equipment that contains sulfur hexafluoride ($SF_6$). Equipment insulated with $SF_6$ is most frequently found at electrical substations. Emissions of $SF_6$ occur as a result of leaking equipment and improper handling practices during servicing and disposal.

Global $SF_6$ emissions from electric power systems (EPSs) are expected to increase through 2030, reaching 64 million metric tons of carbon dioxide equivalent ($MtCO_2e$) (see Figure 10-1). In these projections, China represents a significant share of total emissions by 2030. Brazil, India, South Korea, and the rest of world increase their $SF_6$ emissions marginally, while the United States experiences a decline over the same time period.

Figure 10-1: $SF_6$ Emissions from Electric Power Systems: 2000–2030 ($MtCO_2e$)



Source: U.S. Environmental Protection Agency (USEPA), 2012

The following technologies and handling practices can be implemented to reduce both causes of emissions—leaking equipment and improper handling:

- **Leak detection and leak repair (LDAR)**: Various monitoring and repair methods reduce gas leakage from gaskets and faulty seals in equipment.
- **Equipment refurbishment**: Refurbishing old equipment reduces longer-term leakage problems that cannot be addressed sufficiently by LDAR.
- **$SF_6$ recycling**: Technicians transfer $SF_6$ to special gas carts prior to maintenance or decommissioning, reducing emissions that would otherwise result from the venting of $SF_6$ to the atmosphere.
- **Improved $SF_6$ handling**: Employee training efforts that improve general handling practices of $SF_6$ to reduce and avoid instances such as accidentally venting the gas, using inappropriate

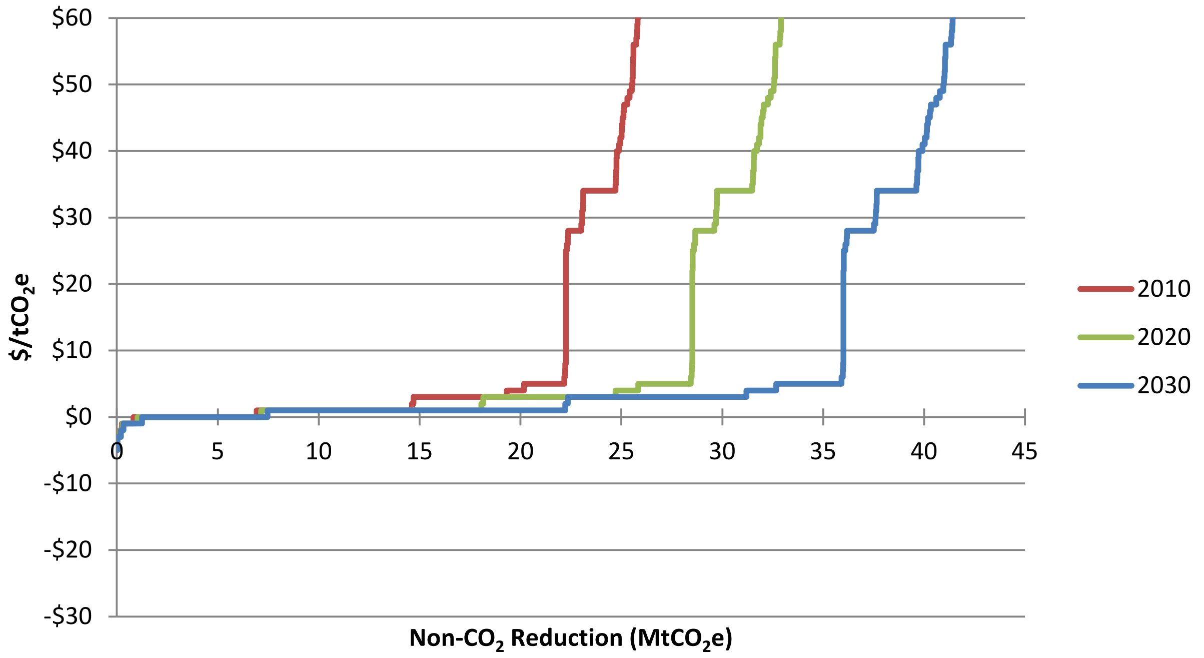
fittings to connect transfer hoses to cylinders or equipment, misplacing gas cylinders, and other similar situations that result in handling losses.

Europe and Japan have largely adopted emission reduction measures to the greatest extent possible; it is believed that few opportunities remain for reduction; data reported to the UNFCCC indicate a downward trend of emissions within the last decade (UNFCCC, 2009). In the United States, $SF_6$ recycling is widely used, but there remains significant potential for reductions through other measures, particularly improved $SF_6$ handling. In the developing world, $SF_6$ recycling is rarely conducted; therefore, there are significant opportunities for reductions from increased $SF_6$ recycling in addition to significant reduction opportunities from improved $SF_6$ handling (NCGC, 2010; NEPA, 2005). The most cost-effective reductions can be achieved by improving general $SF_6$ handling practices at EPSs in the developing world. In these cases, the cost per ton is −\$1.20/t$CO_2$e. The most expensive emission reductions for the developing world are from implementing LDAR at \$1.98/t$CO_2$e. Opportunities to reduce emissions in the United States are more expensive, expected to range from −\$0.20/t$CO_2$e for improved $SF_6$ handling to \$9.40/t$CO_2$e for equipment refurbishment.

The manufacture of equipment for electrical transmission and distribution can also result in $SF_6$ emissions, but this type of emission is not included in this assessment.

The global abatement potential in the EPS sector is 42.8 Mt$CO_2$e in 2030, which represents 67% of projected baseline emissions. This represents the maximum level of reductions that are technically achievable by applying the four abatement measures in the EPS sector. For example, leak detection and leak repair is assumed to have a reduction efficiency of 50%, and is applied only to a the stream of emissions that occur due to periodic leakage; other options have a greater reduction efficiency, but no options are available to reduce 100% of emissions from all emission streams. Figure 10-2 presents the global marginal abatement cost (MAC) curves charting the potential emission reductions in 2010, 2020, and 2030.

**Figure 10-2: Global Abatement Potential in Electric Power Systems: 2010, 2020, and 2030**



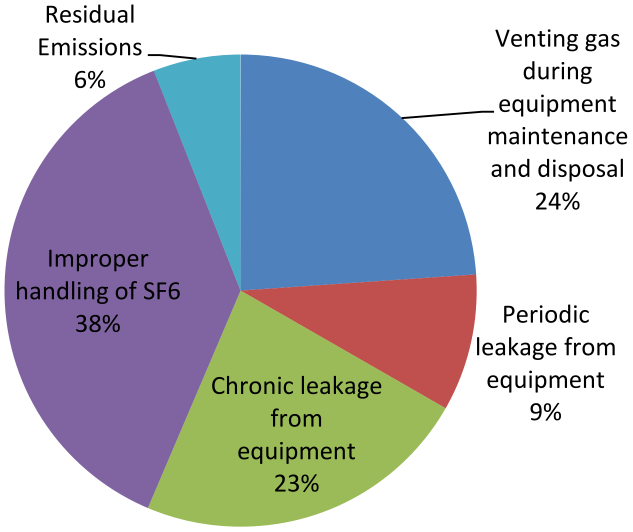
In 2030, approximately 7.5 $MtCO_2e$, or a 12% reduction in baseline emissions, is technically achievable at a break-even price of $0/$tCO_2e$. At $5/$tCO_2e$, an additional 28 $MtCO_2e$ may be reduced, equating to a cumulative reduction of 56% of the global emissions baseline. The remaining reductions of 7 $MtCO_2e$ are available at incrementally higher prices.

In the following sections of this chapter, we first characterize the source of $SF_6$ emissions in the EPS sector and the trends driving future emissions projections. Next, we discuss the projected baselines from 2010 to 2030. This is followed by a description of the abatement measures' engineering and cost assumptions assumed for this analysis. Section IV.10.4 presents the additional assumptions used in the MAC analysis unique to the EPS sector. The final section presents the MAC results in more detail and discusses some of the uncertainties and limitations to the analysis.

## IV.10.2 $SF_6$ Emissions from Electric Power Systems

Emissions of $SF_6$ from electrical equipment used in EPSs broadly occur through two routes: equipment leakage and handling losses. Leakage losses can occur at gasket seals, flanges, and threaded fittings and are generally larger in older equipment. Emissions from improper handling can include intentional venting to the atmosphere or unintentional venting, such as transferring $SF_6$ between containers and equipment using improperly attached or improperly sized fittings. Figure 10-3 presents the global distribution of $SF_6$ emissions by emission stream assumed for this analysis. Leakage losses correspond to periodic leakage from equipment (9%) and chronic leakage from equipment (23%). Improper handling and venting losses correspond to venting gas during equipment maintenance and disposal and improper handling. The break-out percentages are based on assumptions used to develop the technical applicability of the options identified to mitigate these emission streams.

**Figure 10-3: Percentage of Global $SF_6$ Emissions in 2020 by Emission Stream (% of GWP-Weighted Emissions)**



The amount of $SF_6$ gas that each piece of electrical transmission and distribution equipment can hold when properly insulated is referred to as "nameplate capacity," which is measured in pounds or kilograms of the gas. For the purpose of evaluating the cost of reducing $SF_6$ emissions from EPSs, this analysis considers reduction costs for a typical electric transmission and distribution system that uses $SF_6$-insulated electrical equipment totaling 100,000 pounds of nameplate capacity. The system includes a variety of $SF_6$-insulated electrical equipment (including circuit breakers, circuit switchers, and gas-insulated substations), although the vast majority of $SF_6$ is contained in high voltage circuit breakers. Circuit breakers within the system are assumed to be produced by ABB, Alstom, HVB AE, Mitsubishi, and Siemens, with an equal proportion of breakers from each manufacturer.

The analysis considers several possibilities for the maintenance and $SF_6$ handling procedures used at the typical electric transmission and distribution system, reflecting different levels of emissions. For the purpose of this analysis, the three types of systems include the following:

- **Residual emissions system**: In Europe and Japan, abatement options are close to fully implemented. Therefore, a residual emissions system represents an EPS containing $SF_6$-insulated equipment located in Europe or Japan.
- **Uncontrolled system**: In contrast, abatement options have only been minimally applied or not applied at all in most developing countries (Czerepuszko, 2011a; NCGC, 2010; NEPA, 2005; Rothlisberger, 2011a). Therefore, the uncontrolled abatement system represents an EPS containing $SF_6$-insulated equipment located in a developing country, which for this analysis would mean any country outside of Europe, Japan, and the United States.[1]
- **Partially controlled system**: Abatement options have been partially to fully applied in the United States.[2] The partially controlled system represents an EPS containing $SF_6$-insulated equipment located in the United States.

Figure 10-4 displays the breakdown of global emissions by system type as projected for 2020. For the purpose of this analysis, the uncontrolled systems and partially uncontrolled systems are representative of every system within their identifying regions. Therefore, the engineering cost results will not vary among systems within the developing world or among systems within the United States.

### IV.10.2.1 Activity Data or Important Sectoral or Regional Trends

The key activity data that drives $SF_6$ emissions from EPSs is the amount of $SF_6$-insulated electrical equipment in use; this quantity is important for both leakage and handling losses.

However, data are not available on the total amount of $SF_6$-insulated equipment currently in use or historically in use at the country level. In the absence of such data, changes in the amount of $SF_6$-insulated electrical equipment in use (both historically and in the future) can be estimated from the historical and projected changes in electricity demand at the regional level. This is because electricity demand is correlated with the size of the electrical grid required to service that demand, and the size of the electrical grid is correlated to the amount of $SF_6$ consumed by utilities within the region. Thus, the key activity data used to drive emissions is electricity demand. Other important activity data include the characteristics of the equipment in use (such as age) to estimate leakage emissions and employee training and investments in $SF_6$ handling technologies to estimate handling emissions. In this analysis, these drivers are addressed on a regional level.

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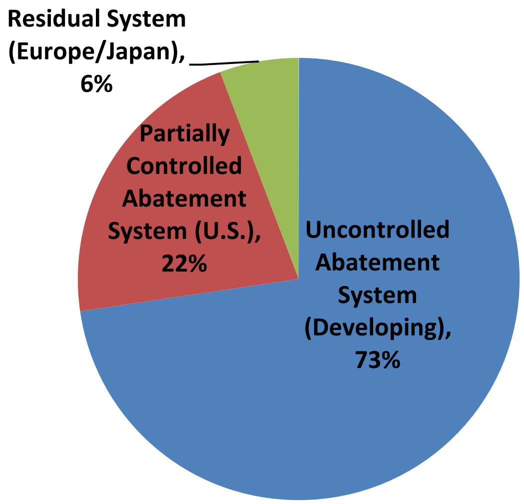
[1] Australia and New Zealand are considered to have uncontrolled systems, which may be one limitation to this assumption.

[2] This system is also assumed for Canada.

**Figure 10-4: Global $SF_6$ Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)**



According to EIA (2009), electricity demand through 2030 is projected to grow two to three times faster in developing countries than developed countries.

### Leakage Emissions

Over the past 30 to 40 years, the amount of $SF_6$ necessary for the operation of switchgear has declined significantly and the tightness of equipment has improved. Such engineering design changes have resulted in smaller leakage amounts and less frequent leakage over time (McCracken et al., 2000; Rhiemeier et al., 2010). The average age of $SF_6$-insulated equipment in developed countries (including Europe, Japan, and the United States) is considerably older than in developing countries. Until recently, developing countries were slow to adopt $SF_6$-insulated equipment because of its relatively high cost compared with other traditional technologies, such as oil-insulated circuit breakers (Rothlisberger, 2011b). Also, the electrical grid in developing countries has grown rapidly over the last decade with economic growth, so the average age of all types of electrical equipment tends to be newer in developing countries than in developed countries, whose electrical grid has historically grown at a more gradual pace. The average $SF_6$-insulated circuit breaker in developing countries, therefore, is assumed to leak less than the average $SF_6$-insulated circuit breaker in developed countries.

### Handling Emissions

Employee training and investments in $SF_6$ handling technologies (such as $SF_6$ recovery carts) vary widely among countries and regions. The use of equipment and accessories to properly handle $SF_6$ is high in developed countries (Rothlisberger, 2011a) yet low to nonexistent in at least some developing countries (NCGC, 2010; NEPA, 2005). Employee training is perhaps strongest in Europe, where the European Commission requires that personnel who handle $SF_6$ receive formal training and certification (EC Reg. No. 842/2006). In the United States, employee training has improved significantly since 1999 by companies participating in the USEPA's voluntary $SF_6$ Emission Reduction Partnership for Electric Power Systems, but, in general, training is not as rigorous as in Europe, and it is uncertain what level of training (if any) has been instituted by companies not part of the USEPA voluntary program. Employee training is low to nonexistent in at least some developing countries (NEPA, 2005).

### IV.10.2.2 Emission Estimates and Related Assumptions

Global $SF_6$ emissions from EPSs in 2010 were estimated to be 44 $MtCO_2e$, which represents a 10% decrease from 1990 levels. This emissions decline, despite increases in the amount of $SF_6$ in use over the same time period, was based largely on improved management practices and the retirement of old leak-prone equipment in the United States and EU. However, it is estimated that emissions have increased in recent years because of the rapid increase in the amount of $SF_6$-insulated equipment being used in the developing world without the application of $SF_6$ abatement technologies and practices. These emission increases have been offset somewhat by the improved design of modern $SF_6$-insulated equipment being installed in the developing world. But from 2010 to 2030, global $SF_6$ emissions from EPSs are still projected to increase 44% from 44 to 64 $MtCO_2e$ (see Table 10-1), driven largely by increases in emissions from developing countries in Asia.

**Table 10-1: Projected Baseline Emissions from Electric Power Systems: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGRa (2010-2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 12.8 | 15.6 | 18.9 | 22.7 | 26.3 | 3.7% |
| United States | 12.1 | 12.1 | 11.1 | 10.8 | 10.3 | −0.8% |
| India | 2.2 | 2.7 | 3.2 | 3.7 | 4.2 | 3.3% |
| Brazil | 1.6 | 1.9 | 2.2 | 2.5 | 2.8 | 2.7% |
| South Korea | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.3% |
| **Rest of Region** | | | | | | |
| Africa | 1.7 | 2.0 | 2.3 | 2.5 | 2.8 | 2.4% |
| Central and South America | 1.4 | 1.4 | 1.5 | 1.6 | 1.7 | 1.2% |
| Middle East | 2.0 | 2.2 | 2.5 | 2.8 | 3.1 | 2.2% |
| Europe | 3.6 | 3.3 | 3.1 | 2.5 | 2.1 | −2.6% |
| Eurasia | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 0.0% |
| Asia | 3.4 | 3.8 | 4.4 | 4.9 | 5.7 | 2.6% |
| North America | 0.9 | 1.1 | 1.2 | 1.3 | 1.5 | 2.4% |
| **World Total** | **44.2** | **48.8** | **53.2** | **58.4** | **63.8** | **1.8%** |

[a] CAGR= Compound Annual Growth Rate
Source: USEPA. 2012

Historical emission estimates of $SF_6$ from electrical equipment use are available for most developed countries through the UNFCCC flexible query system (UNFCCC, 2009). In the absence of UNFCCC reported data, historical global emissions were estimated using the 2004 RAND survey (Smythe, 2004) of global $SF_6$ sales to electric utilities and estimates of net electricity consumption by region. This method assumes that purchases of $SF_6$ by electric utilities are equal to emissions of $SF_6$ by utilities and that a country's share of global emissions is equal to the country's share of global electricity consumption.[3] Emissions projections are based on projected changes in electricity demand (EIA, 2009) for the country's

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[3] The assumption that $SF_6$ purchases are equal to emissions is conservative in that some EPSs purchase $SF_6$ to fill new equipment rather than to replace $SF_6$ lost through emissions.

region; as described above, changes in electricity demand correlate to changes in the electrical grid, which correlate to changes in $SF_6$ emissions.

## IV.10.3 Abatement Measures and Engineering Cost Analysis

The four abatement options for this sector are $SF_6$ recycling, LDAR, equipment refurbishment, and improved $SF_6$ handling. Replacing existing $SF_6$-insulated equipment with newer equipment that holds less $SF_6$ and is more leak-tight is another possible abatement option; however, this mitigation practice is assumed to already occur in the baseline. Given that the investment to replace a circuit breaker or other $SF_6$-containing equipment can be as high as a million to several million dollars, it is not examined in this analysis for systems located in developing countries. All options are applicable to EPSs that are subject to abatement (those outside of Europe and Japan). For the purpose of this analysis, four distinct emission streams were analyzed for the sector, and each emission stream can only be abated by one of the abatement options (the abatement options are not capable of abating emissions for any of the other streams). Hence, the application of an abatement option to its unique emission stream does not affect the applicability of any other options to their own emission streams. Table 10-2 shows the reduction efficiency used for each abatement option.

**Table 10-2: EPS Abatement Options**

| Abatement Option | Applicable System Types | Reduction Efficiency |
|---|---|---|
| **$SF_6$ Recycling** | Uncontrolled abatement system<br>Partially controlled system | 90% |
| **LDAR** | Uncontrolled system<br>Partially controlled system | 50% |
| **Equipment Refurbishment** | Uncontrolled system<br>Partially controlled system | 95% |
| **Improved $SF_6$ Handling** | Uncontrolled system<br>Partially controlled system | 90% |

Table 10-3 presents the engineering cost data for each mitigation option outlined above, including all cost parameters necessary to calculate the break-even price.

The characteristics, applicability, and key engineering cost results for each abatement option are presented below. For additional information on these technologies see Appendix K.

### IV.10.3.1 $SF_6$ Recycling

This option involves transferring $SF_6$ from electrical equipment into storage containers during equipment servicing or decommissioning so that the $SF_6$ can be reused. Recycling is conducted using an $SF_6$ reclamation cart (commonly referred to as a gas cart). The gas cart recovers the $SF_6$ from the equipment and purifies it for future use; the recovered and purified $SF_6$ gas can then be stored within the cart, in a separate storage container, or transferred back to the equipment for reuse. Proper recycling techniques are documented in technical literature (CIGRE, 2005; IEC, 2008; IEEE, 2012). The alternative to using a gas cart is venting the used $SF_6$ into the atmosphere and then replacing it with fresh $SF_6$. Venting is typically performed in areas where environmental consideration is low because the cost of purchasing new gas is often cheaper than purchasing gas carts and paying technicians to reclaim gas from equipment.

### Table 10-3: Engineering Cost Data on a Facility Basis

| Abatement Option | Project Lifetime (Years) | Capital Cost (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|
| **$SF_6$ Recycling** | 15 | $479,560 | $67,994 | $5,372 | 46,833 |
| | | $71,934 | $6,256 | $19,937 | 8,618 |
| **LDAR** | 5 | $95,420 | $12,592 | $534 | 8,673 |
| | | $91,485 | $3,476 | $6,339 | 4,788 |
| **Equipment Refurbishment** | 20 | $126,069 | $9,570 | — | 6,591 |
| | | $453,849 | $5,283 | — | 7,278 |
| **Improved $SF_6$ Handling** | 1 | $13,526 | $90,659 | $253 | 62,444 |
| | | $13,526 | $25,025 | $2,508 | 34,474 |

The $SF_6$ recycling option addresses emissions that occur if $SF_6$ contained inside equipment is vented directly to the atmosphere, either because the equipment is undergoing a maintenance/repair activity requiring removal of the gas or because the equipment is being decommissioned. Based on expert judgment, $SF_6$ vented to the atmosphere accounts for 30% of emissions from uncontrolled systems (in developing countries) and 10% of emissions from partially controlled systems (in the United States).

$SF_6$ recycling can reduce emissions by 4,320 pounds for the uncontrolled systems and 795 pounds for the partially controlled systems. The lifetime of this abatement option is 15 years (Rothlisberger, 2011a). Cost and revenue estimates for the $SF_6$ recycling option are summarized below:

- **Capital costs.** The average total capital costs associated with the purchase of gas carts were estimated to be about $480,000 for the uncontrolled system and $72,000 for the partially controlled system. The cost per gas cart unit was the same for both systems at approximately $96,000. Gas carts can range in cost from as low as $20,000 to as high as $175,000 depending on their size (Rothlisberger, 2011a), and a mid-range gas cart size was assumed for both system types in this analysis. The average capital costs for the partially controlled system are less than the cost per unit, because U.S. systems have implemented $SF_6$ recycling to a greater extent and fewer gas carts are needed across U.S. systems: less than one per system.
- **Annual operation and maintenance** (**O&M**) **costs.** O&M costs were estimated to be $5,000 for the uncontrolled system and $20,000 for the partially controlled system. The lower O&M costs for the uncontrolled system were driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue.** Annual revenue, which was estimated based on the reduction of $SF_6$ emissions multiplied by the cost per pound of $SF_6$ gas, was close to $68,000 for the uncontrolled system and $6,000 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system because the uncontrolled system has not implemented the option at all, while the partially controlled system has implemented the option to 85% of its potential—therefore the potential for reductions is greater. In addition, the cost of $SF_6$ per pound varies regionally and is relatively low in the United States (Rothlisberger, 2011a), so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 15 years.
- **Reduction Efficiency:** The reduction efficiency for $SF_6$ recycling is 90%.

### IV.10.3.2 Leak Detection and Leak Repair (LDAR)

LDAR is a two-step process. First, a leak detection technique is used to identify gas leaks from $SF_6$-insulated equipment. Leak detection methods vary and can involve simple techniques such as using soap and water solutions to more sophisticated techniques such as those requiring cameras to visualize the source of $SF_6$ leaks by exploiting the strong infrared adsorption of $SF_6$ for detection. Thermal imaging cameras allow the detection of even minor leaks without the need to take equipment out of service. The abatement option analyzed in this analysis is the use of a thermal imaging camera. Identified leaks are typically repaired by applying a sealing material to the component that is leaking, although in some cases the component needs to be replaced completely. The International Council on Large Electric Systems (CIGRE), published “SF6 Tightness Guide” (Brochure No. 430) offers details on more specific methods for leak detection and tightness procedures and test methods (CIGRE, 2010).

Emissions addressed by LDAR occur when a piece of equipment periodically develops a manageable leak from a specific component such as a bushing flange gasket. Once the leak is repaired, the equipment tends to last months to years without another major leak. $SF_6$ emissions from periodic equipment leakage account for 10% of emissions from both uncontrolled systems (in developing countries) and partially controlled systems (in the United States) (Rothlisberger, 2011a; 2011b).

Emission reductions from LDAR were estimated to be 800 pounds for the uncontrolled system and 440 pounds for the partially controlled system. The lifetime of this abatement option is five years (Czerepuszko, 2011a). Cost and revenue estimates for LDAR are summarized below:

- **Capital costs.** The capital costs associated with purchasing thermal imaging cameras were estimated to be $95,000 for an uncontrolled abatement system and $91,000 for a partially controlled system. The cost for a single thermal imaging camera was approximately $98,000 (Czerepuszko, 2011a).
- **Annual O&M costs.** O&M costs were estimated to be $540 for the uncontrolled system and $6,300 for the partially controlled system. The lower O&M costs for the uncontrolled system were driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of $SF_6$ emissions multiplied by the cost per pound of $SF_6$ gas, was $12,600 for the uncontrolled system and $3,500 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, because the cost of $SF_6$ per pound varies regionally and costs significantly less in the United States (Rothlisberger, 2011a), the cost of $SF_6$ per pound is significantly less for the partially controlled system relative to systems in other regions, and so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is five years.
- **Reduction Efficiency:** The reduction efficiency for LDAR is 50%.

### IV.10.3.3 Equipment Refurbishment

Unlike LDAR, which tends to focus on small leaks on specific components such as a bushing flange gasket, refurbishment addresses the need for a comprehensive repair from equipment that chronically leaks large amounts of $SF_6$ gas. Refurbishment is a process in which equipment is disassembled and rebuilt (and possibly upgraded) using remachined, cleaned, and/or new components. The option is focused mostly toward dual-pressure circuit breakers built before 1980, which hold large amounts of $SF_6$

and were initially built with gasket material that corroded metal within the breaker (resulting in numerous leaks over time).

Although the leaks can be temporarily repaired using the LDAR option (and often are), using LDAR over time requires high servicing costs because of the extent of the LDAR required and the amount of gas needed to replace the emitted gas. Using LDAR only for this category of equipment also increases the risk for system reliability issues. Ultimately the equipment needs to be refurbished or replaced for these issues to be solved.

Based on expert judgment, $SF_6$ from chronically leaking equipment accounts for 20% of emissions from uncontrolled systems (in developing countries) and 40% of emissions from partially controlled systems (in the United States).

Emission reductions from equipment refurbishment were estimated to be 600 pounds for the uncontrolled system and 670 pounds for the partially controlled system. The lifetime of this abatement option was estimated to be 20 years based on the assumption that the average lifetime of new equipment was 40 years, and the lifetime of refurbished equipment will be about half that of new equipment. Cost and revenue estimates for equipment refurbishment are summarized below:

- **Capital costs.** The capital costs associated with equipment refurbishment were estimated to be \$125,000 for an uncontrolled system and \$450,000 for a partially controlled system. The estimated cost to replace a single 1,130-pound nameplate capacity circuit breaker was estimated to be \$143,000 (developed from McCracken et al. [2000]).
- **Annual O&M costs.** It was assumed that the equipment refurbishment is conducted off-site of the system facility by the manufacturer and that there are no incremental O&M costs associated with the equipment after it has been refurbished and returned to the EPS.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of $SF_6$ emissions multiplied by the cost per pound of $SF_6$ gas, was \$9,600 for the uncontrolled system and \$5,300 for the partially controlled system. Annual revenues are significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, the cost of $SF_6$ per pound is significantly less for the partially controlled system, so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 20 years.
- **Reduction Efficiency:** The reduction efficiency for equipment refurbishment is 95%.

#### IV.10.3.4 Improved $SF_6$ Handling

This option involves improving the procedures and techniques for handling $SF_6$, especially when maintenance is being performed on gas-insulated circuit breakers. Handling-related leaks can occur when (1) inappropriate fittings are used to connect transfer hoses to cylinders or equipment; (2) $SF_6$ is not cleared from transfer hoses before the hoses are disconnected from cylinders/equipment; (3) gas cylinders are not monitored/maintained because they have been misplaced or stored improperly; and (4) any time $SF_6$ is accidently vented by a technician. Improving $SF_6$ handling involves both training technicians to properly handle gas and purchasing adapter kits that ensure proper fittings are available for connecting hoses to all gas-insulated equipment throughout the system.

$SF_6$ emissions from handling-related leaks account for 40% of emissions from both uncontrolled systems (in developing countries) and partially controlled systems (in the United States) (Rothlisberger, 2011a; 2011b).

Employee training and investments in $SF_6$ handling technologies (such as $SF_6$ recovery carts) are measures that improve $SF_6$ handling; several technical references are available with detailed guidance on the proper techniques for recovering, disposing and other handling practices of $SF_6$ gas (CIGRE, 2005; IEC, 2008; IEEE, 2012). Emission reductions from improved $SF_6$ handling were estimated to be 5,800 pounds for the uncontrolled system and 3,200 pounds for the partially controlled system. The lifetime of this abatement option was one year, with training conducted on an annual basis (Rothlisberger, 2011a). Cost and revenue estimates for the improved $SF_6$ handling option are summarized below:

- **Capital costs.** The capital costs associated with improved $SF_6$ handling were estimated to be \$13,500 for both the uncontrolled system and the partially controlled system. This capital cost consists entirely of purchasing adapter kits, which were estimated to cost \$1,350 each (middle of cost range provided by Rothlisberger [2011a]).
- **Annual O&M costs.** O&M costs were estimated to be \$250 for the uncontrolled system and \$2,500 for the partially controlled system. The lower O&M cost for the uncontrolled system was driven by the significantly lower labor cost in developing countries relative to the United States.
- **Annual revenue**. Annual revenue, which was estimated based on the reduction of $SF_6$ emissions multiplied by the cost per pound of $SF_6$ gas, was \$91,000 for the uncontrolled system and \$25,000 for the partially controlled system. Annual revenue was significantly higher for the uncontrolled system primarily because it was assumed that the uncontrolled system has implemented the option to a lesser extent than the partially controlled system—therefore the potential for reductions is greater. In addition, the cost of $SF_6$ per pound is significantly less for the partially controlled system, so less money is saved through reduced emissions.
- **Technical Lifetime:** The technical lifetime of this option is 1 year.
- **Reduction Efficiency:** The reduction efficiency for improved $SF_6$ handling is 90%.

## IV.10.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for $SF_6$ emissions reduction.

### IV.10.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section for two types of EPS systems, defined earlier as uncontrolled and partially controlled systems, to calculate a break-even price for the options available for each EPS system.

### IV.10.4.2 Definition of EPS Model Facilities

#### *Key Characteristics of the Residual Emissions System*

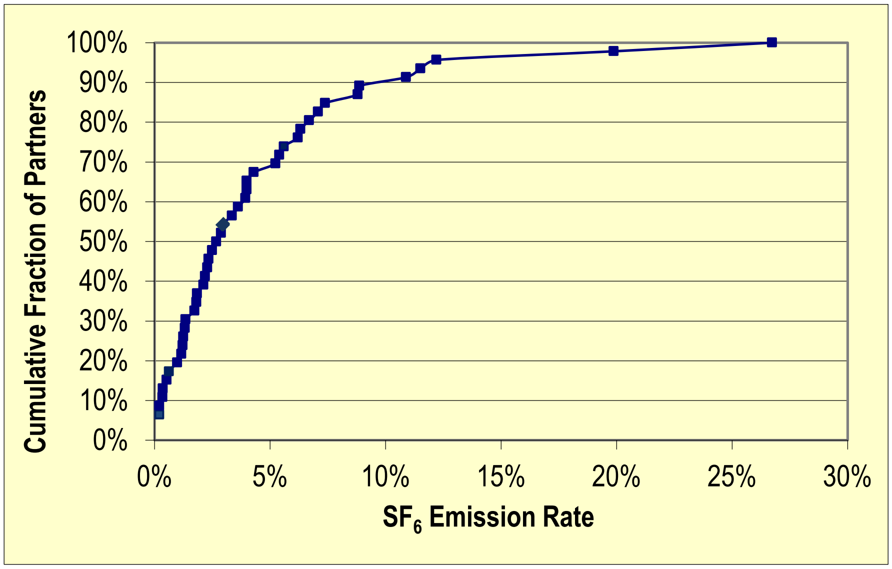
Facilities in Europe and Japan have been classified as residual emission systems. In these regions, abatement options are close to fully implemented. The vast majority of the $SF_6$ emissions that do occur are considered residual emissions from occurrences such as catastrophic equipment failure and accidents associated with gas handling (Rhiemeier et al., 2010). Japanese equipment designs and maintenance practices are believed to be similar to those in Europe (Yokota et al., 2005). Country-reported data as reported in UNFCCC inventory submissions for Europe and Japan show that $SF_6$ emissions from electric power systems have declined from 1990 through 2003. Emissions are expected to continue to decline in these regions as utilities, through government-sponsored voluntary and mandatory programs, implement reduction measures such as leak detection and repair and gas recycling practices (USEPA, 2012).

### Key Characteristics of the Partially Controlled System

In the last decade, electric utilities have begun to voluntarily reduce SF$_6$ emissions by applying the abatement options included in this analysis (USEPA, 2011a). The baseline emission projections for the partially controlled system were developed under the assumption that the adoption of abatement technologies and practices in the United States will continue to grow into the future (as it has over the last decade through voluntary efforts such as USEPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems). For purposes of the engineering cost analysis, the emission rate for the partially controlled system was 8.8%, which was the average U.S. emission rate in 2009 as estimated by USEPA (2011b). The size of the partially controlled system was a typical medium-sized facility with 100,000 pounds of installed SF$_6$ nameplate capacity. The size of the system was chosen to yield realistic nominal abatement and cost values because the size of a system in the United States does not significantly influence the system's emission rate, baseline abatement levels, or other key characteristics.

Figure 10-5 presents 2010 emission rates from EPSs that participate in the USEPA voluntary Partnership. Emission rates reported through the Partnership contributed to the average U.S. emission rate of 8.8% used in this analysis (USEPA, 2011a).

**Figure 10-5: Distribution of 2010 Emission Rates Reported through USEPA's Voluntary Partnership**



Source: USEPA, 2011a

### Key Characteristics of the Uncontrolled System

The baseline emission projections for developing countries were developed under the assumption that the application of abatement technologies does not increase in the future. For purposes of the engineering cost analysis, the assumed emission rate for the uncontrolled system was 16%, which is approximately double the U.S. emission rate. The emission rate for the developing world is very uncertain because a published emission rate based on actual measurements of emissions is not known. The 16% emission rate was developed by considering a probable emission rate for an EPS in the United States (for which emission rates are available) if that system had similar characteristics to the average system in the developing world. The size of the uncontrolled system was a typical medium-sized system with 100,000 pounds of installed $SF_6$ nameplate capacity. The size of the system was chosen simply to yield realistic nominal abatement and cost values because the size of a system in developing countries does not significantly influence the system's emission rate, baseline abatement levels, or other key characteristics.

Table 10-4 lists the countries or regions associated with each model facility system. The residual emissions systems include Japan and Europe, which includes a majority of European Union member countries, in additional to Norway and Switzerland. The United States and Canada represent partially controlled systems, and the rest of the world reflects uncontrolled systems.

**Table 10-4: EPSs System Country Mapping**

| Residual Emission Systems | | | Partially Controlled | Uncontrolled Systems |
|---|---|---|---|---|
| **Japan** | | | **United States** | **Rest of World** |
| **Europe** | | | **Canada** | |
| Austria | Greece | Portugal | | |
| Belgium | Hungary | Romania | | |
| Bulgaria | Ireland | Slovakia | | |
| Cyprus | Italy | Slovenia | | |
| Czech Republic | Latvia | Spain | | |
| Denmark | Lithuania | Sweden | | |
| Estonia | Luxembourg | Switzerland | | |
| Finland | Netherlands | United Kingdom | | |
| France | Norway | | | |
| Germany | Poland | | | |

### IV.10.4.3 Parameters Used to Estimate Technical Effectiveness

The analysis also developed a technical effectiveness parameter, defined as the percentage reductions achievable by each abatement measure/system type combination. Estimating this parameter requires making a number of assumptions regarding estimates of technical applicability, market penetration, and reduction efficiency. These assumptions are held constant for all model years. Table 10-5 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness.

### IV.10.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits and technical lifetime as described in Section IV.10.3 to calculate the break-even price for each mitigation option at each model facility. Table 10-6 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Improved $SF_6$ handling is the only options with a negative break-even price, also known as a "no-regrets" option because the benefits of adopting the abatement measure outweigh the costs of implementation. The remaining three options have break-even prices greater than $0/$tCO_2$e.

Table 10-5: Technical Effectiveness Summary

| Abatement Option | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
|---|---|---|---|---|
| **Developing Countries** | | | | |
| $SF_6$ Recycling | 30% | 100% | 90% | **27%** |
| LDAR | 10% | 100% | 50% | **5%** |
| Equipment Refurbishment | 20% | 20% | 95% | **4%** |
| Improved $SF_6$ Handling | 40% | 100% | 90% | **36%** |
| **United States/Canada** | | | | |
| $SF_6$ Recycling | 10% | 100% | 90% | **9%** |
| LDAR | 10% | 100% | 50% | **5%** |
| Equipment Refurbishment | 40% | 20% | 95% | **8%** |
| Improved $SF_6$ Handling | 40% | 100% | 90% | **36%** |

Table 10-6: Example Break-Even Prices for Abatement Measures in EPSs

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($/$tCO_2e$) | Net Annual Cost ($/$tCO_2e$) | Tax Benefit of Depreciation ($/$tCO_2e$) | Break Even Price[a] ($/$tCO_2e$) |
|---|---|---|---|---|---|
| **Developing Countries** | | | | | |
| $SF_6$ Recycling | 46,833 | $2.2 | −$1.3 | $0.5 | **$0.45** |
| LDAR | 8,673 | $4.8 | −$1.4 | $1.5 | **$1.98** |
| Equipment Refurbishment | 6,591 | $3.7 | −$1.5 | $0.6 | **$1.65** |
| Improved $SF_6$ Handling | 62,444 | $0.4 | −$1.4 | $0.1 | **−$1.20** |
| **United States/Canada** | | | | | |
| $SF_6$ Recycling | 8,618 | $1.8 | $1.6 | $0.4 | **$3.05** |
| LDAR | 4,788 | $8.4 | $0.6 | $2.5 | **$6.45** |
| Equipment Refurbishment | 7,278 | $12.2 | −$0.7 | $2.1 | **$9.40** |
| Improved $SF_6$ Handling | 34,474 | $0.7 | −$0.7 | $0.3 | **−$0.20** |

[a] Break-even prices were calculated using a tax rate of 40% and a discount rate of 10%.

### IV.10.4.5 MAC Analysis Results

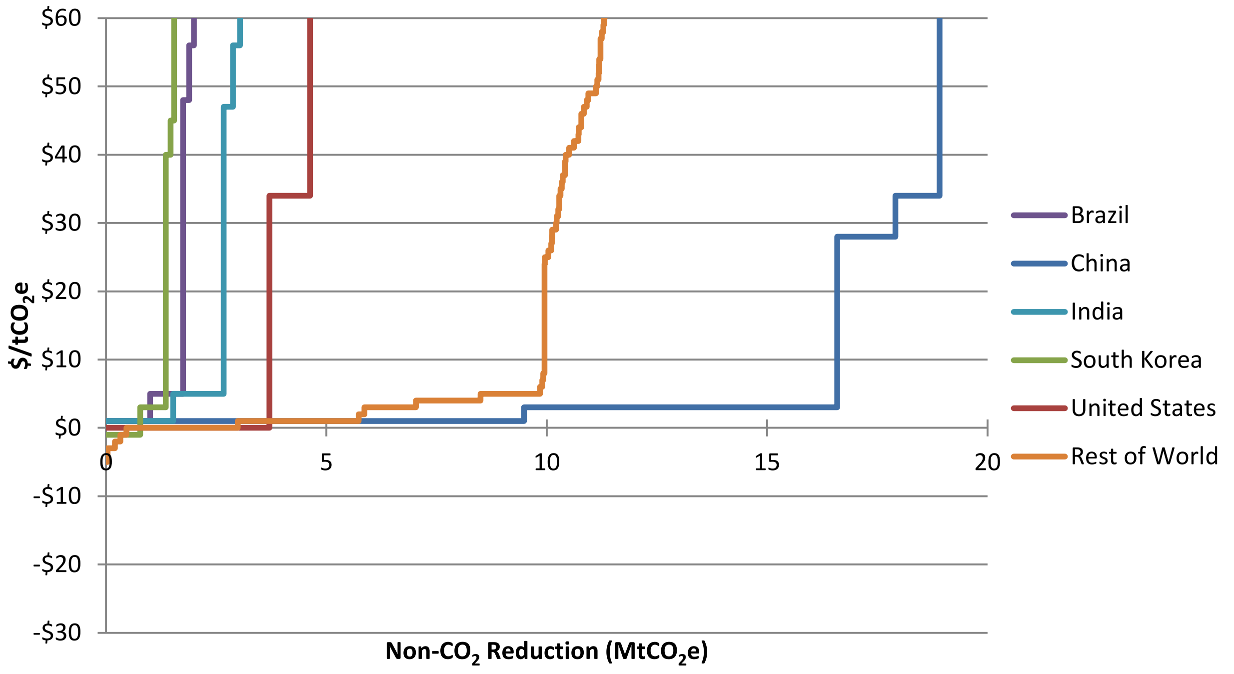
The global abatement potential for $SF_6$ reductions in the EPS sector is estimated to be 43 $MtCO_2e$, which is 67% of total projected emissions in 2030. Table 10-7 presents the cumulative reductions achieved at selected break-even prices. Figure 10-6 shows the MAC curve for the top five emitting countries in the EPS sector. Over 83% of the maximum abatement potential is achieved at break-even prices below $5/$tCO_2e$ in 2030.

**Table 10-7: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break Even Price ($\$/tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Country/Region** | **10** | **5** | **0** | **5** | **10** | **15** | **20** | **30** | **50** | **100** | **100+** |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| Brazil | — | — | — | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.9 | 2.0 | 2.0 |
| China | — | — | — | 16.6 | 16.6 | 16.6 | 16.6 | 17.9 | 18.9 | 18.9 | 18.9 |
| India | — | — | — | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.9 | 3.0 | 3.0 |
| South Korea | — | — | 0.8 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 | 1.5 | 1.5 |
| United States | — | — | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 4.6 | 4.6 | 5.9 |
| **Rest of Regions** | | | | | | | | | | | |
| Africa | — | — | 0.6 | 1.8 | 1.8 | 1.8 | 1.8 | 2.0 | 2.0 | 2.0 | 2.0 |
| Central and South America | — | — | 0.4 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 |
| Middle East | — | 0.0 | 0.7 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 2.2 | 2.2 | 2.2 |
| Europe | — | — | 0.3 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 |
| Eurasia | — | — | 0.1 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 |
| Asia | — | — | 0.4 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.4 | 3.4 | 3.4 |
| North America | — | — | 0.5 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 |
| **World Total** | **—** | **0.0** | **7.5** | **35.9** | **36.0** | **36.0** | **36.0** | **37.6** | **41.0** | **41.5** | **42.8** |

[a] The World Total may not equal the sum of the country and region break-even prices due to small differences in rounding.

**Figure 10-6: Marginal Abatement Cost Curves for Top Five and Rest of World Emitters in 2030**



## IV.10.5 Uncertainties and Limitations

Despite a comprehensive literature review and correspondence with some of the most knowledgeable representatives from the electric power transmission and distribution industry, considerable uncertainty is associated with some of the engineering cost data used for this analysis. Emission data account for the greatest area of uncertainty.

We are not aware of any published information on emission levels or rates in the developing world that are based on actual measurements. Also, there is very limited information on the distribution of emissions within a typical EPS because the system-level mass-balance approach (currently the standard emissions monitoring method) does not track where or how emissions occur. The lack of reliable continuous emission monitoring methods at specific points within EPSs also makes it difficult to accurately monitor the reduction efficiencies associated with specific abatement options, so the reduction efficiencies used for this analysis are based on judgments from industry experts rather than the studies involving emissions monitoring. Much less uncertainty is associated with cost data because most cost data were obtained directly from industry representatives that provide the equipment and services for abating emissions.

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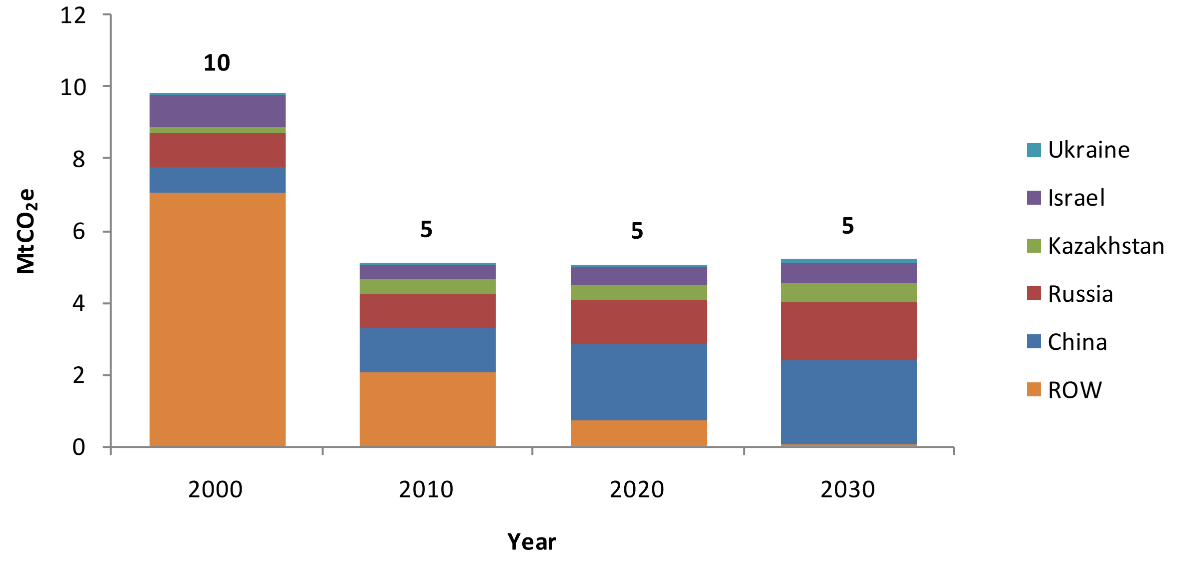
# IV.11. $SF_6$ Emissions from Magnesium Production

## IV.11.1 Sector Summary

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

Between 2000 and 2010, global $SF_6$ emissions from magnesium manufacturing have decreased 50%, from 10 million metric tons of carbon dioxide equivalent ($MtCO_2e$) to 5 $MtCO_2e$ (USEPA, 2012). Over this time period, magnesium production has increased, but growth has been offset by major initiatives to phase out the use of $SF_6$ in magnesium production in numerous countries. As Figure 11-1 shows, from 2010 to 2030, emissions from magnesium production are projected to stay in the range of approximately 5 $MtCO_2e$ (USEPA, 2012).

Figure 11-1: $SF_6$ Emissions from Magnesium Production: 2000–2030 ($MtCO_2e$)

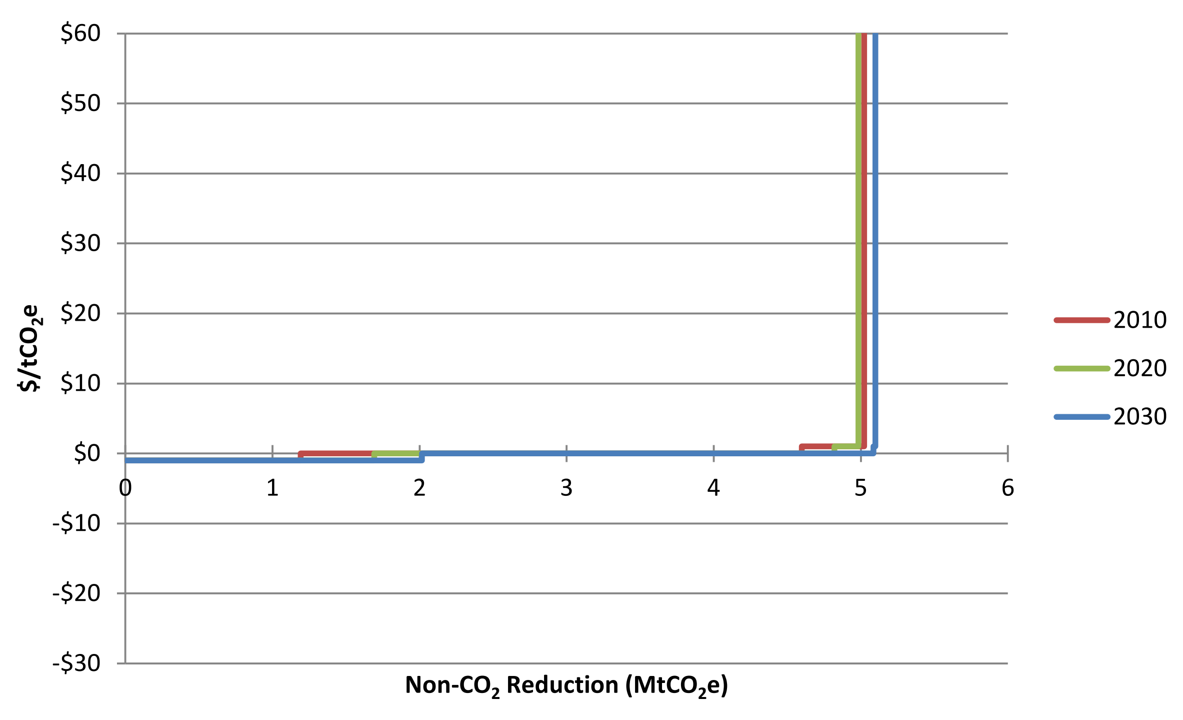


ROW = Rest of World

Source: U.S. Environmental Protection Agency (USEPA), 2012.

Global abatement potential of $SF_6$ in the magnesium manufacturing sector is 5 $MtCO_2e$ in 2030, which is approximately 98% of the projected emissions. Figure 11-2 presents the sector marginal abatement cost (MAC) curves for 2010, 2020, and 2030. Three potential options are available for reducing $SF_6$ emissions from magnesium production and processing operations. These emission abatement measures all include substituting $SF_6$ with an alternate cover gas: $SO_2$, HFC-134a, or Novec™ 612.

**Figure 11-2: Global Abatement Potential in Magnesium Manufacturing: 2010, 2020, and 2030**



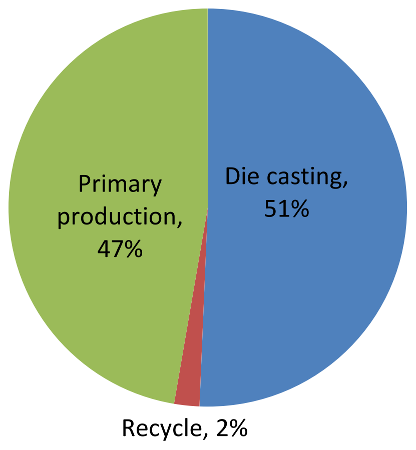
This chapter follows a structure similar to previous chapters, starting with a description of the industrial activity, facility types, and source of emissions, followed by a discussion of the projected emissions out to 2030. Section IV.11.3 characterizes the abatement measures by providing a brief description of each option and information on their costs and performance assumptions. The chapter concludes with a discussion of regional MAC results.

## IV.11.2 $SF_6$ Emissions from Magnesium Manufacturing

Use of $SF_6$ as a cover gas is the only source of emissions from magnesium production. Although studies indicate some destruction of $SF_6$ in its use as a cover gas (Bartos et al., 2003), the analysis described here follows current Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006), which assumes that all $SF_6$ used is emitted to the atmosphere. This analysis uses three model facilities to define magnesium production across die casting, primary production, and reprocessing (recycle/remelt) facilities. Global $SF_6$ emissions from magnesium production by facility type are shown in Figure 11-3. Model facilities are based on industry data from the United States, but apply to magnesium facilities globally.

For the purpose of evaluating the cost of reducing $SF_6$ emissions from magnesium production, this analysis considers reduction costs for three typical magnesium production facilities—die casting, recycle/remelt, and primary production, which were generally characterized based on facility-specific case studies measuring average $SF_6$ consumption, production capacity, and type. We characterize these typical facilities as follows:

Figure 11-3: Global $SF_6$ Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)



- **Die Casting Facility:** This model facility represents a medium-sized die casting facility. The facility is characterized based on real data from a case study (USEPA, 2011) where a given abatement option was implemented in 2008. The facility produces 26,014 metric tons of magnesium per year, and emits 0.17 kg of $SF_6$ per metric ton of magnesium produced, representing a total annual facility emission of 4,483 kg of $SF_6$. Production and emissions data from 2007 is used to define the pre-abatement emissions baseline (USEPA, 2011). Emissions data was reported by the facility based on its consumption of $SF_6$, assuming all $SF_6$ used is emitted to the atmosphere.
- **Recycle/Remelt Facility:** This model facility represents a medium-sized recycle facility. The facility is characterized based on real data from a case study where a given abatement option was implemented in 2008. The facility produces 18,453 metric tons of magnesium per year, and emits 1.09 kg of $SF_6$ per metric ton of magnesium produced, representing a total annual facility emission of 20,026 kg of $SF_6$. Production and emissions data from 2007 is used to define the pre-abatement emissions baseline (USEPA, 2011). Emissions data were reported by the facility based on its consumption of $SF_6$, assuming all $SF_6$ used is emitted to the atmosphere.
- **Primary Production Facility:** Assumes the same characteristics as the die casting facility.

### IV.11.2.1 Activity Data or Important Sectoral or Regional Trends

The primary activity data for this sector are the quantities of magnesium produced or processed. Between 1990 and 2010, global $SF_6$ emissions from magnesium manufacturing have decreased 58%, from 12 $MtCO_2e$ to 5 $MtCO_2e$ (USEPA, 2012). Over this time period, magnesium production has increased, but this growth has been offset by major initiatives to phase out the use of $SF_6$ in magnesium production in numerous countries.

From 2010 to 2030, emissions from magnesium production are projected to stay in the range of approximately 5 $MtCO_2e$ (USEPA, 2012). Emissions from Organisation for Economic Co-operation and Development (OECD) countries decrease substantially in the short term because of facility closures in North America and $SF_6$ phaseout efforts (U.S. Geological Survey [USGS], 2011). As a result, the OECD share of global $SF_6$ emissions from magnesium manufacturing is projected to decrease from 40% in 2010 to 12% in 2030. Major $SF_6$ phaseout efforts are driven by the USEPA's voluntary partnership in the United States, and the regulatory directives in Japan and Europe.

$SF_6$ emissions from magnesium manufacturing in non-OECD Asia are projected to increase significantly between 2010 and 2030, increasing the region's global share of emissions from 20% to 44%. Emissions in the non-OECD Europe and Eurasia region experience similar growth. The overall increase in non-OECD Asia's share of global emissions results from an increase in Chinese primary magnesium production and die casting fueled by local and foreign investment. China's emissions growth is driven by their die casting operations as well as by the share of China's primary production (approximately 10%) that is assumed to use $SF_6$ as the cover gas mechanism. Emissions from Central and South America are driven by production in Brazil. Brazil's emissions were estimated to have declined considerably since implementation of a Clean Development Mechanism project after 2005 involving a switch to $SO_2$ as the cover gas (UNFCCC, 2010).

### IV.11.2.2 Emission Estimates and Related Assumptions

Global emissions from the magnesium production sector were 5.13 $MtCO_2e$ in 2010, growing to 5.22 $MtCO_2e$ in 2030. Emission estimates for U.S facilities were based on magnesium production statistics and specific emissions factors for each manufacturing process using data from the USEPA $SF_6$ Emission Reduction Partnership (USEPA, 2011) and USGS (2011). As per IPCC 2006 guidelines, it is assumed that all $SF_6$ used as a cover gas is emitted. Data used in this analysis on magnesium production and cover gas use for a typical facility were taken from a case study on U.S. facilities (USEPA, 2011) and may vary for facilities in other countries. Table 11-1 presents projected emissions between 2010 and 2030 by country and region.

**Table 11-1: Projected Baseline Emissions from Magnesium Production: 2010–2030 ($MtCO_2e$)**

| Country/Region | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010 2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 1.2 | 1.6 | 2.1 | 2.2 | 2.3 | 3.2% |
| Russia | 0.9 | 1.1 | 1.2 | 1.4 | 1.6 | 2.6% |
| Kazakhstan | 0.4 | 0.5 | 0.5 | 0.5 | 0.6 | 1.7% |
| Israel | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 1.7% |
| Ukraine | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 1.7% |
| **Rest of Region** | | | | | | |
| Africa | — | — | — | — | — | — |
| Central and South America | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | — |
| Middle East | — | — | — | — | — | — |
| Europe | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | −22.2% |
| Eurasia | — | — | — | — | — | — |
| Asia | 0.6 | 0.6 | 0.6 | 0.0 | 0.0 | −20.8% |
| North America | 1.3 | 0.4 | 0.2 | 0.1 | 0.1 | −13.3% |
| **World Total** | **5.1** | **4.6** | **5.1** | **4.8** | **5.2** | **0.1%** |

[a] CAGR = Compound Annual Growth Rate

Source: USEPA, 2012

## IV.11.3 Abatement Measures and Engineering Cost Analysis

Three potential options are available for reducing $SF_6$ emissions from magnesium production and processing operations. These emission abatement measures all include replacing $SF_6$ with an alternative cover gas: $SO_2$, HFC-134a, or Novec™ 612. Table 11-2 presents the reduction efficiency and applicability for the three alternative cover gas options.

The remainder of this section provides an overview of each abatement option and details the cost and reduction assumptions.

**Table 11-2: Magnesium Production Abatement Options**

| Abatement Option | Reduction Efficiency | Applicability |
|---|---|---|
| **Alternative cover gas—Novec™ 612** | 100% | Die casting |
| | | Recycle/remelt |
| | | Primary production |
| **Alternative cover gas—HFC-134a** | 95% | Die casting |
| | | Recycle/remelt |
| | | Primary production |
| **Alternative cover gas—$SO_2$** | 100% | Die casting |
| | | Recycle/remelt |
| | | Primary production |

### IV.11.3.1 Replacement with Alternative Cover Gas—Sulfur Dioxide ($SO_2$)

Historically, $SO_2$ has been used as a cover gas in magnesium production and processing activities. However, because of toxicity, odor, and corrosivity concerns, $SO_2$ use was discontinued in most countries. Current $SO_2$ technology research aims to improve process feed systems and control technology, as well as to address the toxicity and odor issues with improved containment and pollution control systems (Environment Canada, 1998). The use of $SO_2$ has the potential to reduce $SF_6$ emissions by 100% because a complete replacement of the cover gas system is involved. Currently, $SO_2$ is being used as a cover gas; for example, it is used as a cover gas at one diecasting facility in Brazil (UNFCCC, 2010). This option is assumed to be technically applicable to all three model facilities. The maximum market penetration for this option is assumed to be 80% of the emissions of $SF_6$ for recycle/remelt facilities, and 10% for both die casting and primary production facilities. The lifetime of this option is assumed to be 15 years.

Facilities implementing $SO_2$ as an alternative cover gas incur capital costs related to the cost for new piping, pollution control equipment, and safety equipment for workers. The total capital cost was \$490,781 for all three facility types. Facilities also incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. This option results in annual gas purchase costs of \$16,763 each for die casting and primary production facilities and an annual gas purchase cost of \$74,833 for recycle/remelt facilities. $SO_2$ is significantly less expensive than $SF_6$, and the required gas replacement ratio is 1:1, resulting in a significant net savings in material costs. Replacing $SF_6$ with $SO_2$ also results in avoided costs of \$131,633 each for both die casting and primary production model facilities and \$588,018 for the recycle/remelt model facility associated with the purchase of $SF_6$.

### IV.11.3.2 Replacement with Alternative Cover Gas—HFC 134a

Research has shown that candidate fluorinated compounds such as HFC-134a can be a cover gas substitute for $SF_6$ (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). In addition, currently, HFC-134a is used as a cover gas at two diecasting facilities in Israel (UNFCCC, 2008a, 2008b).While fluorinated gases have an advantage over $SO_2$ because they have potentially fewer associated health, safety, odor, and corrosive impacts, some current fluorinated gas alternatives (including HFC-134a) still have global warming potential (GWP). However, the GWP of HFC-134a is significantly less than that of $SF_6$: thus, the GWP-weighted cover gas emissions could be reduced by 95%. HFC-134a is assumed to be technically applicable to all model facilities. The maximum market penetration for this option is assumed to be 45% of the emissions of $SF_6$ for die casting and primary production facilities, and 10% for recycle/remelt facilities. The lifetime of this option is assumed to be 15 years.

Facilities implementing HFC-134a as an alternative cover gas do not incur up-front capital costs, as use of HFC-134a is a simple drop-in option and does not require additional/new systems or training. They incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. Use of HFC-134a results in annual gas purchase costs of $32,908 each for die casting and primary production facilities and $147,005 for the recycle/remelt facility. HFC-134a is not only less expensive than $SF_6$, but additionally HFC-134a has a gas replacement ratio of 0.5:1, resulting in significant net savings in material costs. Replacing $SF_6$ with HFC-134a results in avoided costs of $131,633 each for both die casting and primary production model facilities and $588,018 for the recycle/remelt facility associated with the purchase of $SF_6$.

### IV.11.3.3 Replacement with Alternative Cover Gas—Novec™ 612

Research has shown that candidate fluorinated compounds such as Novec™ 612 can be a cover gas substitute for $SF_6$ (Milbrath, 2002; Ricketts, 2002; Hillis, 2002). Additionally, currently, Novec™612 is being used at one die casting facility in the United States. The use of Novec™ 612 as an alternative cover gas represents an advantage over $SO_2$ because, like other fluorinated gases, Novec™ 612 has potentially fewer associated health, safety, odor, and corrosive impacts. Novec™ 612 is a zero GWP gas and therefore has a reduction efficiency of 100% compared with $SF_6$. Novec™ 612 is assumed to be technically applicable to all model facilities.

Facilities implementing Novec™ 612 as an alternative cover gas incur capital costs related to the purchase of computerized mass flow control cabinets and piping material to direct the gas. The total capital cost was $245,390 for the die casting facility, $33,128 for the recycle/remelt facility, and $496,916 for the primary production facility. Facilities also incur annual costs (or generate annual cost savings) based on the purchase price of the alternate cover gas. Use of Novec™612 results in annual gas purchase costs of $60,754 for die casting and primary production facilities and $271,393 for the recycle/remelt facility. However, because the replacement ratio of Novec™ 612 to $SF_6$ is 0.3:1, significantly less Novec™ 612 is required to process the same quantity of magnesium. These costs are offset by the avoided costs of purchasing $SF_6$, an annual cost savings of $131,633 for both die casting and primary production model facilities and $588,018 for the recycle/remelt model facility.

### IV.11.3.4 Summary of Mitigation Technology Costs and Characteristics

Table 11-3 presents all of the data needed to calculate the break-even price for the options analyzed. All options have an assumed lifetime of 15 years.

Table 11-3: Engineering Cost Data on a Facility Basis

| Abatement Option | Facility Type | Project Lifetime (Years) | Capital Costs (2010 USD) | Annual Savings* (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|---|
| $SO_2$ | Die casting | 15 | $490,781 | $131,633 | $16,763 | 107,144 |
| | Recycle/remelt | 15 | $490,781 | $588,018 | $74,883 | 478,621 |
| | Primary production | 15 | $490,781 | $131,633 | $16,763 | 107,144 |
| HFC-134a | Die casting | 15 | — | $131,633 | $32,908 | 101,316 |
| | Recycle/remelt | 15 | — | $588,018 | $147,005 | 452,588 |
| | Primary production | 15 | — | $131,633 | $32,908 | 101,316 |
| Novec™ 612 | Die casting | 15 | $245,390 | $131,633 | $60,754 | 107,139 |
| | Recycle/remelt | 15 | $33,128 | $588,018 | $271,393 | 478,601 |
| | Primary production | 15 | 496,916 | $131,633 | $60,754 | 107,139 |

* These numbers are not net annual savings.

## IV.11.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for magnesium production.

### IV.11.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at three magnesium production facility types to calculate a break-even price for each option at each facility (i.e., die casting, recycle/remelt, and primary production). This section presents detailed information on how each type of facility was defined in this analysis and detailed information on how costs were built out for each mitigation technology.

### IV.11.4.2 Model Facilities Defined

The break-even cost analysis is conducted on three model facility types defined as follows:

- **Die casting facility**—Represents medium-sized facility currently in production in the United States where abatement option was implemented in 2008. Annual production is assumed to be 26 kilo tons. The annual $SF_6$ usage rate was 0.17kg/ ton produced (based on data reported by facility under USEPA $SF_6$ Emission Reduction Partnership). This emission factor multiplied by the annual production of magnesium yields annual facility emissions of approximately 4.4 tons of $SF_6$ (equal to 107,550 $tCO_2e$).
- **Recycle/Remelt facility**—Represents medium-sized facility currently in production in the United States where abatement option was implemented in 2008. Production data is from 2007, prior to implementation of abatement option. Annual production is assumed to be 18 kilo tons. The annual $SF_6$ usage rate was 1.09 kg/ ton of magnesium produced (based on data reported by facility under USEPA $SF_6$ Emission Reduction Partnership). This emission factor multiplied by the annual production yields annual facility emissions of approximately 20 tons of $SF_6$.
- **Primary production facility**—Assumes similar characteristics as the die casting model facility. Annual magnesium production is 26 kilotons and a $SF_6$ usage rate of 0.17 kg/ton of production. The model primary production facility annual emissions are 4.4 tons of $SF_{6.}$

### IV.11.4.3 Assessment of Technical Effectiveness

For this analysis, we developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/facility-type combination. Table 11-4 lists the assumptions regarding technical applicability, market penetration, and technical effectiveness of each option.

**Table 11-4: Technical Effectiveness Summary**

| Abatement Option | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
|---|---|---|---|---|
| **Die Casting Facility** | | | | |
| Alternative cover gas—Novec™ 612 | 100% | 45% | 100% | **45%** |
| Alternative cover gas—HFC-134a | 100% | 45% | 95% | **43%** |
| Alternative cover gas—$SO_2$ | 100% | 10% | 100% | **10%** |
| **Recycle/Remelt Facility** | | | | |
| Alternative cover gas—Novec™ 612 | 100% | 10% | 100% | **10%** |
| Alternative cover gas—HFC-134a | 100% | 10% | 95% | **9%** |
| Alternative cover gas—$SO_2$ | 100% | 80% | 100% | **80%** |
| **Primary Production Facility** | | | | |
| Alternative cover gas—Novec™ 612 | 100% | 45% | 100% | **45%** |
| Alternative cover gas—HFC-134a | 100% | 45% | 95% | **43%** |
| Alternative cover gas—$SO_2$ | 100% | 10% | 100% | **10%** |

We assume that all three abatement measures are technically applicable to all facility types, hence the technical applicability factor of 100%. Market penetration rates were assumed based on expert judgment. For example, for die casting facility experts believe that a facility would adopt both Novec™612 and HFC-134a over $SO_2$, with an equal chance of adopting either Novec™612 or HFC-134a. The same assumptions were made for a primary production facility. For recycle/remelt facility, experts believed that there would be a preference for $SO_2$ over the other two alternative cover gases, with an equal chance of adopting either Novec™612 or HFC-134a. Multiplying the technical applicability, market penetration, and reduction efficiency for each alternative cover gas at each facility type produces the technical effectiveness estimates for each facility type. These assumptions are held constant for all model years.

### IV.11.4.4 Estimating Abatement Project Costs and Benefits

The MAC model uses the estimated abatement project costs and benefits as described in Section IV.11.3 to calculate the break-even price for each mitigation option at each model facility. Table 11-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD. Die casting and recycle facility types have negative break-even prices for all three abatement measures. The only positive break-even price estimated was for alternate cover gas—Novec™ 612 when applied to the primary production facility due to a higher initial capital cost compared with other facility types. The remaining two abatement measures applied to the primary production facility have negative break-even prices.

### IV.11.4.5 MAC Analysis Results

The global abatement potential for $SF_6$ reductions in the magnesium manufacturing sector is estimated to be 98% of total projected emissions in 2030. Table 11-6 presents the cumulative reductions achieved at selected break-even prices. Figure 11-4 shows the MAC curve for the top five emitting countries for this sector. Total abatement potential is achieved at break-even prices below $5/tCO$_2$e in 2030.

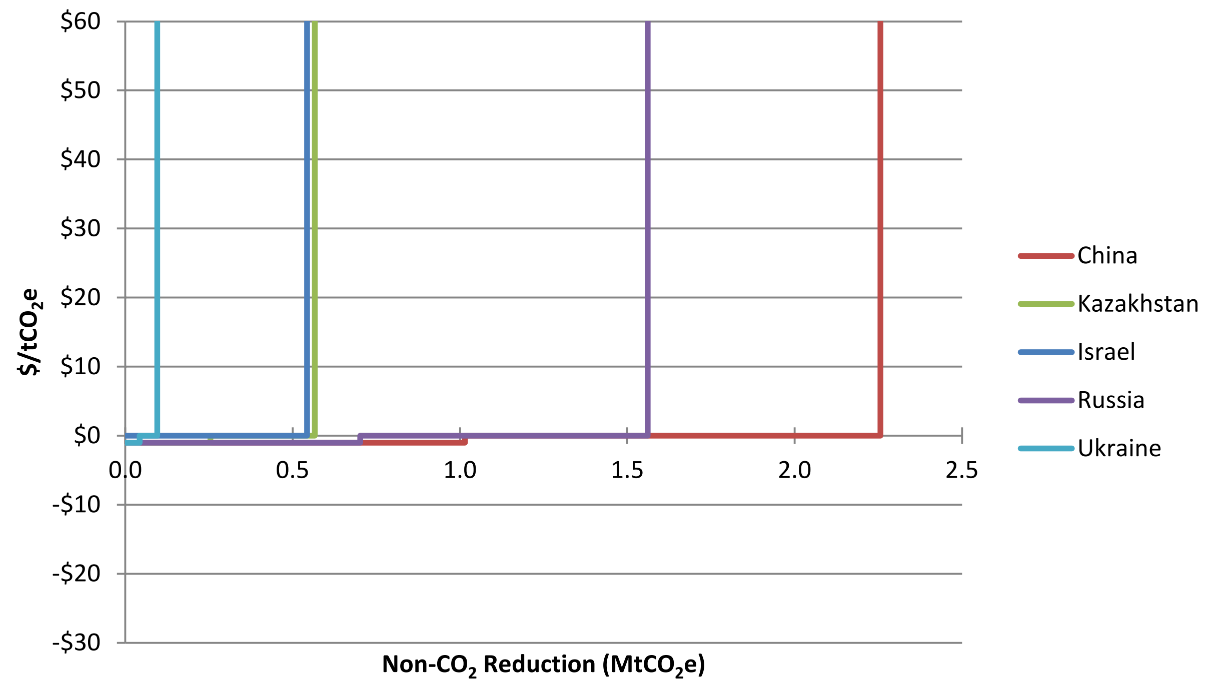
### Table 11-5: Example Break-Even Prices for Abatement Measures in Magnesium Manufacturing

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break-Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Die Casting Facility** | | | | | |
| Alternative cover gas—Novec™ 612 | 107,139 | $0.50 | −$0.66 | $0.10 | **−$0.26** |
| Alternative cover gas—HFC-134a | 104,230 | $0.00 | −$0.95 | $0.00 | **−$0.95** |
| Alternative cover gas—$SO_2$ | 107,144 | $1.00 | −$1.07 | $0.20 | **−$0.27** |
| **Recycle/Remelt Facility** | | | | | |
| Alternative cover gas—Novec™ 612 | 478,601 | $0.02 | −$0.66 | $0.00 | **−$0.65** |
| Alternative cover gas—HFC-134a | 465,605 | $0.00 | −$0.95 | $0.00 | **−$0.95** |
| Alternative cover gas—$SO_2$ | 478,621 | $0.22 | −$1.07 | $0.05 | **−$0.89** |
| **Primary Production Facility** | | | | | |
| Alternative cover gas—Novec™612 | 107,139 | $1.02 | −$0.66 | $0.21 | **$0.15** |
| Alternative cover gas—HFC-134a | 104,230 | $0.00 | −$0.95 | $0.00 | **−$0.95** |
| Alternative cover gas—$SO_2$ | 107,144 | $1.00 | −$1.07 | $0.20 | **−$0.27** |

### Table 11-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

| | Break Even Price ($\$/tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | 10 | 5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | — | — | — | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| Israel | — | — | — | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Kazakhstan | — | — | — | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Russia | — | — | — | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Ukraine | — | — | — | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | — | — | — | — | — | — | — | — |
| Central and South America | — | — | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Middle East | — | — | — | — | — | — | — | — | — | — | — |
| Europe | — | — | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Eurasia | — | — | — | — | — | — | — | — | — | — | — |
| Asia | — | — | — | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| North America | — | — | — | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **World Total** | **—** | **—** | **—** | **5.1** | **5.1** | **5.1** | **5.1** | **5.1** | **5.1** | **5.1** | **5.1** |

**Figure 11-4: Marginal Abatement Cost Curves for Top Five Emitters in 2030**



## IV.11.5 Uncertainties and Limitations

As per IPCC guidelines (2006), this analysis assumes that all cover gas used is emitted during magnesium production. However, any $SF_6$ destruction that occurs during use would result in lower emission estimates than currently assumed in this analysis. In addition, this analysis uses data available from U.S. facilities that implemented the three abatement options available. Although the data are representative of abatement costs for U.S. facilities, the data may not be equally applicable to facilities in other countries. Finally, uncertainties are associated with the emission estimates, which are detailed in the Global Emissions Report.

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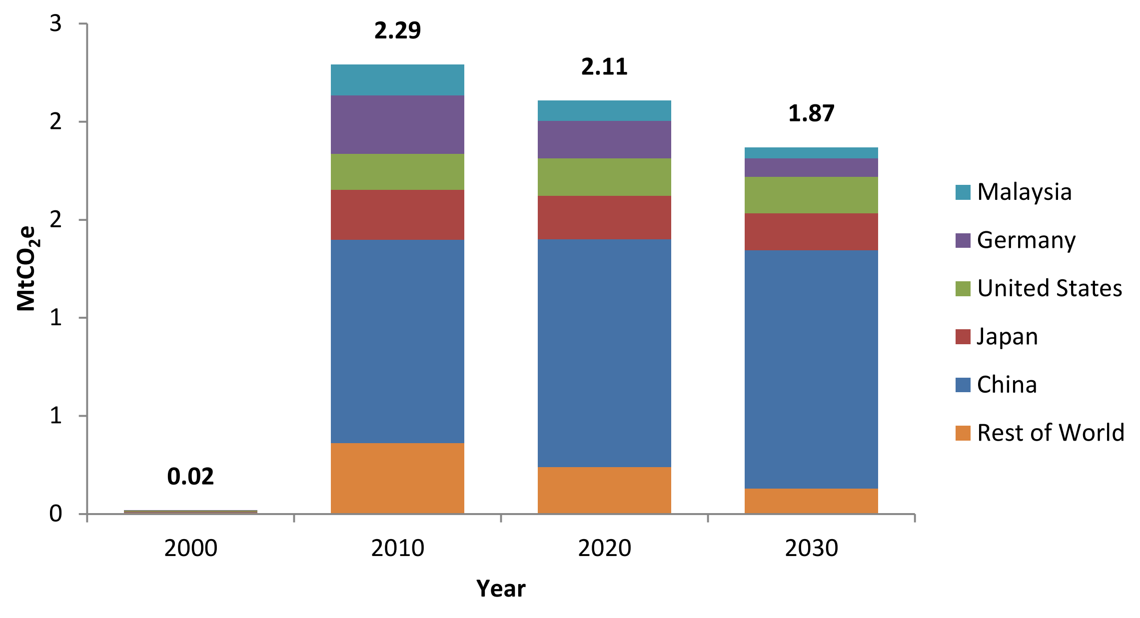
# IV.12. Emissions from Photovoltaic Cell Manufacturing

## IV.12.1 Sector Summary

The photovoltaic (PV) cell manufacturing process can use multiple fluorinated greenhouse gases (F-GHGs) during production, including nitrogen trifluoride ($NF_3$) and the perfluorocompounds (PFCs) carbon tetrafluoride ($CF_4$) and perfluoroethane ($C_2F_6$,). During the manufacture of PV cells some of the F-GHGs not used in processes are released to the atmosphere.

F-GHG emissions from PV cell manufacturing are estimated to be approximately 2.3 million metric tons of carbon dioxide equivalents ($MtCO_2e$) in 2010. As Figure 12-1 shows, by 2030, emissions from the manufacturing of PV cells are expected to decrease to 1.9 $MtCO_2e$. The baseline projections presented here are updated relative to those presented in *Global Anthropogenic Non-$CO_2$ Greenhouse Gas Emissions: 1990 to 2030* (USEPA, 2012). The updates incorporate new market information which has resulted in significantly lower emission estimates. The decrease in emissions can be attributed to lower expected growth in production and lower fraction of production assumed to use F-GHGs. Emissions projections for this sector are particularly uncertain to due limited information on emissions rates, use of fluorinated gases, production growth rates, and policies to encourage renewable energy development.

**Figure 12-1: F-GHG Emissions from PV Cell Manufacturing: 2000–2030 ($MtCO_2e$)**

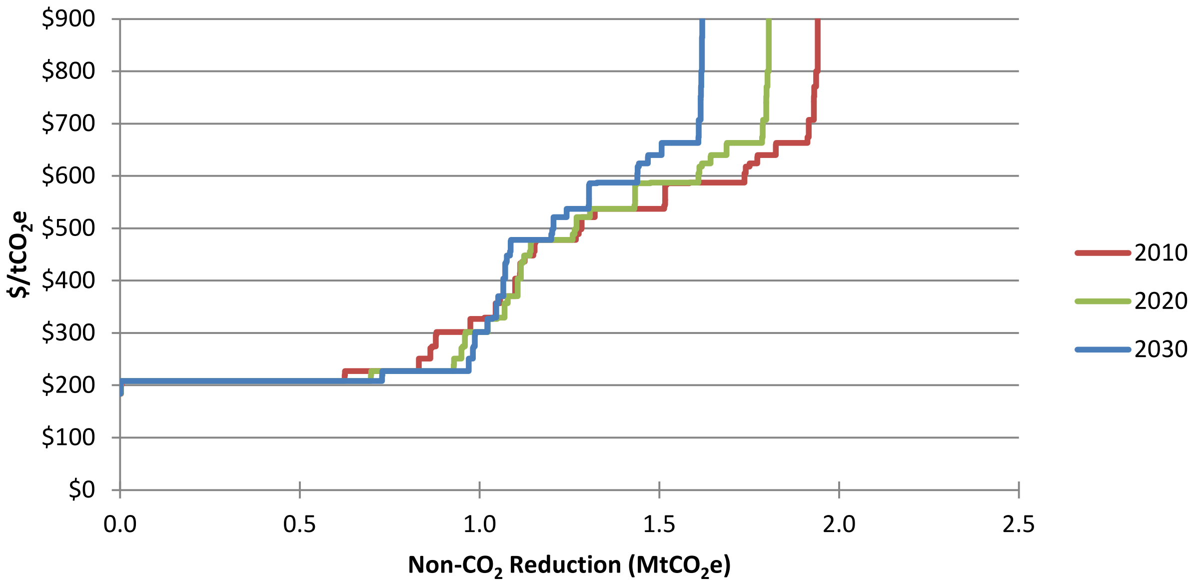


Source: Update of projections presented in USEPA, 2012.

Four mitigation technologies were considered in this analysis as options for reducing F-GHG emissions from PV manufacturing: thermal abatement systems, catalytic abatement systems, plasmas abatement systems, and the $NF_3$ remote chamber clean process. Due to the lack of mitigation cost information specific to PV production, data is drawn from experience reducing emissions from similar processes in semiconductor manufacturing.

The marginal abatement cost (MAC) analysis estimates a global mitigation potential of 1.7 $MtCO_2e$, based on the four abatement measures. The abatement potential represents 90% of the projected emissions in 2030. Figure 12-2 presents the global MAC curves for 2010, 2020, and 2030 for the PV manufacturing sector.

**Figure 12-2: Global Abatement Potential in PV Cell Manufacturing: 2010, 2020, and 2030**



High capital costs and relatively low emissions reduction amounts result in relatively high break-even prices for abatement measures in the PV manufacturing sector relative to other industrial process sectors. As a result, break-even prices in this sector are all greater than $120/$tCO_2e$.

The following sections of this chapter first describe the activities and sources of F-GHG emissions in the PV manufacturing sector and present the projected emissions for 2010 to 2030. Subsequent sections characterize the four abatement measures considered and present the engineering cost assumptions used in the MAC analysis. This is followed by a discussion of the MAC modeling assumptions that were used to estimate the global abatement potential. We conclude the chapter by presenting the MAC curves for a select number of individual countries and discuss some of the major uncertainties and limitations.

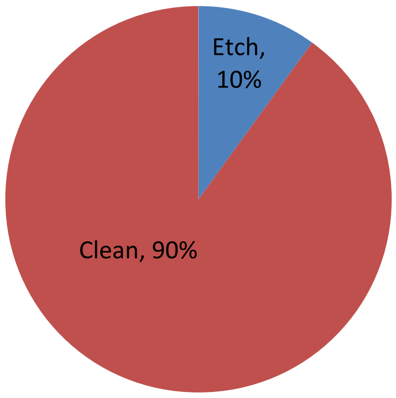
## IV.12.2 Emissions from Photovoltaic Cell Manufacturing

PV manufacturing may use F-GHGs, thereby resulting in F-GHG emissions, including $CF_4$, $C_2F_6$, and $NF_3$, from etching and chamber cleaning processes used during the manufacture of PV cells. Etching is done on various substrates, including crystalline silicon, amorphous silicon, and other thin-films. $CF_4$ and $C_2F_6$ are used during the manufacture of some crystalline silicon (c-Si) PV cells, and $NF_3$ is used during the manufacture of amorphous silicon (a-Si) and tandem a-Si/nanocrystaline (nc) silicon PV cells. However, not all poly-silicon manufacturing process use F-GHGs, this was taken into consideration in the analysis. Processes for PV cells manufactured on other thin films do not require the use of GHGs; therefore, these processes were not considered in this analysis.

The emission estimates presented in Figure 12-1 represent a piece of the total life cycle emissions associated with manufacturing PV cells. One motivation of using PV cells is the production of reliable low carbon energy, so it is not only important to consider the life cycle GHG emissions but also to consider the benefits from using PV cells versus traditional fossil generated power. The European Photovoltaic Industry Association (EPIA) analyzed the life cycle of a PV cell (from material sourcing, through manufacturing, transportation, construction, operation, dismantling and to product collection and recycling into account) and estimated that "The carbon footprint of PV systems—assuming a location in southern Europe—ranges from 16 to 32 $gCO_2$ eq. per kWh compared to between 300 and 1000 g $CO_2$ eq. per kWh when produced from fossil fuels." EPIA also estimates that solar power will still have a carbon footprint of 10 to 20 times less than traditional fossil-based power with carbon capture and storage. While solar power is a good low-carbon alternative to fossil based power and over the lifetime of the cell it has climate benefits over traditional power sources, there is still potential to make it even more beneficial. According to EPIA "The carbon footprint of PV has decreased by approximately 50% in the last 10 years thanks to performance improvements, raw material savings and manufacturing process improvements" (EPIA, 2011). Implementing PFC and $NF_3$ mitigation strategies offers an opportunity to further decrease the carbon footprint of PV cells, particularly given the high potency of these gases.

To evaluate the cost of reducing F-GHG emissions from the manufacture of PV cells, this analysis considers the emissions and reduction costs for a typical PV manufacturing facility, characterized based on an average facility capacity and the applicability of various mitigation technologies to etch and clean emissions. The facility has an average capacity of 80 megawatts (MW) with an estimated 25 tools with 3.5 chambers. The facility uses only three F-GHGs: $CF_4$, $C_2F_6$, and $NF_3$.[1] Figure 12-3 shows the breakdown of etch and clean emissions for the typical facility.

**Figure 12-3: Global F-GHG Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)**



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[1] Although these gases are used for different PV technologies, for simplicity in this analysis, one general facility producing an unidentifiable PV technology was considered.

### IV.12.2.1 Activity Data and Important Sectoral/Regional Trends

Several industry trends which will influence future emissions from this sector include the rate of growth in PV panel production, the overall penetration of PV into the global energy market, and the relative proportion of various PV technologies with different rates of F-gas usage or emissions rates.

Current market trends indicate an increase and then a dip in production, and therefore, increases followed by decreases in annual emissions. Despite many slowing sectors because of the global economic slowdown, the PV sector continued to exceed expected growth rates while other sectors saw slowdowns. According to the *Global Market Outlook for Photovoltaics Until 2016*, the main reasons for the large historic and continued growth in the PV sector are: 1. "Renewable energy has continued to prove itself to be a mainstream energy source and a significant contributor to achieving energy, environmental and economic goals"; 2. "Some countries have increased their focus on renewable energy standards in the wake of the Fukushima nuclear disaster, requiring them to consider new policies that move the market in this direction"; 3. "PV modules have undergone significant price decreases…"; and 4. "In some countries, questions about the future of support-scheme levels has produced boom-and-bust cycles." Also, many countries are just starting to tap into the installed potential for PV. These factors account for the fact that there was large general growth across all regions of the world. However, in 2012, the Congressional Research Service noted that "The creation of incentives for solar installations in several countries around 2004 led many companies to enter the PV industry. According to an estimate by Photon International, more than 1,000 PV module manufacturers worldwide supplied the market in 2011. But with demand in some countries declining and prices weak, the industry appears to have entered a phase of rapid consolidation on a global basis" (CRS, 2012).

The world saw booms in PV cell manufacturing and installation. This growth however, led to an oversupply of panels starting in 2011. Balancing out supply with demand for solar panels has and resulted in factories to close, and will also result in a continued decrease in manufacturing (Forbes, 2012). There is significant uncertainty in whether production levels will remain relatively constant in the future or resume the rapid annual increases which the industry experienced prior to 2011.

The projections presented in this chapter assume that production levels will be sufficient to achieve the cumulative installed capacities from the "New Policy" Scenario of World Energy Outlook 2012, without accounting for installed capacity replacement. These assumptions result in annual production in 2030 decreased to 22.6 GW compared to 24.6 GW in 2010. While there is a growth in demand for solar energy, reflected in forecasted growth in total global installed solar capacity from about 38 gigawatts (GW) in 2010 to 491 GW in 2030 (IEA, 2012), this is expected to be met through already existing uninstalled stock of solar panels and future annual production. Figure 12-1 presents the business as usual emissions from 2000 to 2030 for the five largest emitting countries and the rest of world (ROW). Uncertainty regarding future policies, panel prices, and PV technology improvement result in particularly uncertain projections of future production and associated emissions.

### IV.12.2.2 Emissions Estimates and Related Assumptions

Emissions resulting from PV manufacturing processes were estimated using projected PV cumulative installed capacities from the New Policy Scenario of World Energy Outlook, 2012; capacity and efficiency data from the DisplaySearch PV Database; an assumed solar constant of 1,000 watts per meter squared; Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors for PV manufacturing; and an $NF_3$ emission factor from Fthenakis et al. (2010) and an emission factor developed using sensitive process information. There is little to no variation in manufacturing processes and practices or in emissions trends on a regional basis.

F-GHG emissions from PV manufacturing are estimated to be approximately 2.29 $MtCO_2e$ in 2010. By 2030, emissions from manufacturing PV cells are expected to decrease to 1.87 $MtCO_2e$. This decrease can be attributed to the decrease in the annual PV production for 2030 compared to 2010. The annual production in 2030 is expected to decrease to 22.6 GW compared to 24.6 GW in 2010.

In December of 2012 EPA published the *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990–2030.* The baseline emission estimates presented in this analysis have been revised, and the revised estimates are used for the MAC analysis presented in this report. Like the previous estimates, since little literature is available describing the mitigation activities in the PV cell manufacturing sector, and unlike the semiconductor and FPD manufacturing sectors, the PV manufacturing sector has not set a voluntary reduction goal, the revised estimates do not include assumptions about the use of mitigation technologies for crystalline silicon type manufacturing. However, unlike the previous estimates, the baseline now assumes that half of the production process for amorphous silicon (a-Si) use abatement based on new literature published (Fthenakis et al., 2010). The baseline also assumes that half of the production process for crystalline silicon (c-Si) technology uses and emits $CF_4$ and $C_2F_6$ during manufacturing, as not all PV processes use F-GHGs.

The projected revised emissions are estimated based on annual PV production, differentiated by type of technology, country, and the emission factors for respective types. However, now the future annual PV production is estimated from the projected cumulative installed capacity obtained from World Energy Outlook, New Policy Scenario (IEA, 2012) as opposed to assumed growth rates. The total annual PV production is then differentiated into various types by dividing the total according technology proportions: 77% crystalline Silicon (c-Si), 12% amorphous Silicon (a-Si) and the rest Cadmium Telluride, Copper Indium Gallium Selenide and other categories, which are from the DisplaySearch database (DisplaySearch, 2009). Similarly, the capacity is apportioned by country based on the DisplaySearch database (DisplaySearch, 2009). Like the previous baseline methodology, PV production capacity for each country for historic years was extracted from DisplaySearch database (DisplaySearch, 2009). The area of cell produced is estimated based on the cell efficiency, using new data obtained from IEA Solar Photovoltaic Roadmap (IEA, 2010), and an assumed solar constant of 1000 $W/m^2$.

The $NF_3$ emission factor for a-Si has been updated in the revised baseline estimation methodology. For the a-Si technology, it was assumed that all facilities use $NF_3$ and out of those, 50% of the facilities have abatement devices installed. The emission factor for abated facilities was derived from data presented in literature looking at lifecycle $NF_3$ emissions of PV cells (Fthenakis et al., 2010). The emission factor for unabated facilities was developed using sensitive process information. Lastly, the revised baseline assumes that only 50% of c-Si technology is assumed to use and emit F-GHGs during manufacturing and none of the other technologies are assumed to use and emit F-GHGs.

## IV.12.3 Abatement Measures and Engineering Cost Analysis

Four mitigation technology options were identified for the PV manufacturing sector: thermal abatement, catalytic abatement, plasma abatement, and $NF_3$ remote chamber clean.

- **Thermal abatement**: These point-of-use abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through abatement systems with catalysts (e.g., CuO, ZnO, $Al_2O_3$) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma in a point-of-use abatement system is used to react (destroy or remove) F-GHGs from the process effluent stream.

**Table 12-1: Projected Baseline Emissions from PV Cell Manufacturing: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010  2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 1.0 | 1.2 | 1.2 | 1.1 | 1.2 | 0.8% |
| Japan | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | −1.5% |
| United States | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1% |
| Germany | 0.3 | 0.3 | 0.2 | 0.1 | 0.1 | −5.6% |
| Malaysia | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | −5.0% |
| **Rest of Region** | | | | | | |
| Africa | — | — | — | — | — | — |
| Central and South America | — | — | — | — | — | — |
| Middle East | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | −5.0% |
| Europe | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | −5.0% |
| Eurasia | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | −5.0% |
| Asia | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | −5.0% |
| North America | — | — | — | — | — | — |
| **World Total** | **2.3** | **2.4** | **2.1** | **1.9** | **1.9** | **−1.0%** |

[a] CAGR= Compound Annual Growth Rate

Source: Updated from projections presented in USEPA, 2012

- **$NF_3$ remote chamber clean**: Highly ionized $NF_3$ is used to clean chemical vapor deposition chambers. This process is highly efficient (~98%), resulting in lower emissions on a mass and $CO_2$ basis than traditional in-situ chamber clean processes with utilization efficiencies around 20% to 50% (IPCC, 2006).

These technologies reduce emissions from either etch or chamber clean processes, or in some cases both. Table 12-2 presents the applicability and the reduction efficiency of each abatement measure. The next sections describe each of these mitigation options and additional detail is provided in Appendix M.

**Table 12-2: PV Cell Manufacturing Abatement Options**

| Abatement Option | Applicable 3s) | Reduction Efficiency | Information Source |
|---|---|---|---|
| **Thermal abatement** | Etch and clean | 95% | Fthenakis (2001), Beu (2005), and USEPA (2009) |
| **Catalytic abatement** | Etch and clean | 99% | Fthenakis (2001), Brown et al. (2012) |
| **Plasma abatement** | Etch | 97% | Fthenakis (2001), Hattori et al. (2006) |
| **$NF_3$ remote chamber clean** | Clean | 95% | Beu (2005) |

### IV.12.3.1 Thermal Abatement

Thermal abatement systems can be used to abate F-GHG emissions from both etching and chamber-cleaning processes. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in some facilities. In addition, these systems require large amounts of cooling water, and the use of the systems result in regulated $NO_x$ emissions.

The total facility capital cost for installing thermal abatement systems is estimated to be $5.7 million. This estimate includes costs for the systems, the necessary ducting, water recirculation and hook up, and natural gas costs (Fthenakis, 2001; Burton, 2003). The annual operating cost is estimated to be $328,860 at the facility level. No annual cost savings are associated with using this technology

### IV.12.3.2 Catalytic Abatement

A catalytic abatement system uses a catalyst to destroy or remove F-GHG emissions from the effluents of both plasma etching and chemical vapor deposition (CVD) chamber-cleaning processes. This type of abatement is applicable at most facilities, but again there may be some space constraints as mentioned for thermal abatement systems. Additionally, because these systems are based on destruction via catalyst, they must be process/stream specific to achieve the 99% emission reductions quoted in the literature and used in this analysis (Fthenakis, 2001; Burton, 2003).

Because catalytic destruction systems operate at relatively low temperatures, their use results in little or no $NO_x$ emissions, and the required amounts of water are low as well. Because of the high cost of catalyst replacement, these systems are the least widely used type of abatement (expert judgment).

The capital cost associated with the purchase and installation of the abatement systems is estimated to be $6.9 million per fab (i.e., facility). To use catalytic abatement systems, facilities must factor in the annual cost of resources such as water, waste chemicals, electricity, and catalyst replacements. To cover these operating expenses, a facility manufacturing PV cells is estimated to incur an annual cost of $455,280. As with other abatement technologies considered in this sector, the use of catalytic abatement systems will not result in annual cost savings.

### IV.12.3.3 Plasma Abatement

These systems are applicable to etch processes in most facilities, with some physical space limitations. (These systems though are relatively smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen ($H_2$), oxygen ($O_2$), water ($H_2O$), or methane ($CH_4$)) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no GWP. After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of PFC molecules (Burton, 2003).

The capital cost for plasma abatement systems is estimated to be $1.8 million per facility (Burton, 2003), which covers the purchase and installation of plasma systems. Plasma abatement systems require an annual operation cost of $1,190 per chamber, which includes general maintenance and use of the systems. Total annual facility costs are $51,850 based on an assumed four chambers per tool and 25 tools per facility. The use of plasma abatement systems will not result in annual cost savings.

### IV.12.3.4 $NF_3$ Remote Chamber Clean

$NF_3$ remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high (~98%) utilization rate of $NF_3$ (IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (The stated utilization is based on utilizations for semiconductor manufacturing; as a result of large gas flows in PV manufacturing, the actual utilization may be lower.) $NF_3$ remote clean systems dissociate $NF_3$ using argon gas and converting the source gas to active F-atoms in the plasma upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine ($F_2$), and other gases, most of which are removed by facility acid scrubber systems.

It is assumed that PV facilities are not "$NF_3$ ready"; in other words, these facilities do not have the current infrastructure to handle the direct installation of $NF_3$ remote systems because this is a relatively new technology. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hook ups and necessary hardware such as manifolds and values. The facility cost is estimated to be \$9.2 million. The annual facility cost for $NF_3$ remote clean is estimated to be \$3.4 million (Burton, 2003). These costs are associated with the purchase of larger volumes of gas ($NF_3$ versus traditional chamber clean gases), general maintenance, and $F_2$ scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

### IV.12.3.5 Summary of Mitigation Technology Costs and Characteristics

Table 12-3 summarizes the information used to estimate the break-even prices in the MAC analysis.

**Table 12-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Project Lifetime (Years) | Capital Costs (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount ($tCO_2e$) |
|---|---|---|---|---|---|
| **Thermal abatement** | 7 | \$5,701,971 | \$0 | \$328,862 | 13,625 |
| **Catalytic abatement** | 7 | \$6,906,594 | \$0 | \$455,277 | 14,199 |
| **Plasma abatement** | 7 | \$1,814,664 | \$0 | \$51,848 | 1,398 |
| **$NF_3$ remote clean** | 25 | \$9,200,867 | \$0 | \$3,374,861 | 14,427 |

## IV.12.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the PV manufacturing sector.

### IV.12.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section of this chapter at two hypothetical facilities to calculate a break-even price for each abatement measure. This section presents how we defined the model facility used in this analysis and the technical effectiveness assumptions used to estimate the incremental reductions for each measure. This section also provides an example of how the break-even prices were calculated for each option.

### IV.12.4.2 Definition of Model Facility

The manufacture of PV uses F-GHGs depending on the particular substrate and process used in the production. Substrates used in the industry include crystalline silicon, amorphous silicon, and other thin films. F-GHGs are used during the manufacture of crystalline silicon (c-Si) PV cells, amorphous silicon (a-Si), and tandem a-Si/nanocrystaline (nc) silicon PV cells. Other thin film PV technologies do not require the use of F-GHGs. As with the other electronics manufacturing sectors, emissions in this sector result from two main types of manufacturing processes: etching substrates and cleaning CVD chambers. Manufacturing processes and uses of GHGs across the industry are generally similar; therefore, only one type of model facility was considered for this analysis.

- **Model:** The model facility is a facility that represents a PV manufacturing facility of average manufacturing capacity (DisplaySearch, 2009) of 80 MW with an estimated 25 tools with 3.5 chambers. The facility uses only three F-GHGs: $CF_4$, $C_2F_6$, and $NF_3$.[2] The emissions breakdown for a PV manufacturing facility is estimated to be 10% etch emissions and 90% clean emissions.

The model facility emission breakdown is essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process.

### IV.12.4.3 Assessment of Technical Effectiveness

Similar to the methods employed for analyzing abatement in the semiconductor manufacturing sector, this analysis developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process combination. Estimating this parameter required making a number of assumptions regarding the distribution of emissions by manufacturing process (etch and clean), in addition to process-specific estimates of technical applicability and market penetration. These assumptions are held constant for all model years. Table 12-4 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

**Table 12-4: Technical Effectiveness Summary**

| | Etch (10%) | | Clean (90%) | | | |
|---|---|---|---|---|---|---|
| Abatement Measure | Technical Applicability | Market Penetration | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
| **Thermal abatement** | 85% | 65% | 85% | 20% | 95% | **20%** |
| **Catalytic abatement** | 85% | 10% | 85% | 10% | 99% | **8%** |
| **Plasma abatement** | 85% | 25% | 0% | 0% | 97% | **2%** |
| **$NF_3$ remote clean** | 0% | 0% | 100% | 70% | 95% | **60%** |

The technical effectiveness is the weighted average of the abatement measures using the emissions attributed to each process (i.e., 10% etching, and 90% cleaning) as the weight multiplied by the product of the technical applicability, market penetration, and reduction efficiency for each abatement measure.

The technical effectiveness estimates are then multiplied by the share of total emissions to estimate the abatement potential achievable under each abatement measure.

### IV.12.4.4 Estimating the Break-Even Price of Abatement Measures

The MAC model uses the estimated abatement project costs and benefits as described in Section 12.3 to calculate the break-even price for each abatement measure. Table 12-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

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[2] Although these gases are used for different PV technologies, for simplicity in this analysis, one general facility producing an unidentifiable PV technology was considered.

Table 12-5: Example Break-Even Prices for Abatement Measures in PV Cell Manufacturing

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break Even Price[a] ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| **Thermal abatement** | 13,625 | $143 | $24 | $40 | $128 |
| **Catalytic abatement** | 14,199 | $167 | $32 | $46 | $152 |
| **Plasma abatement** | 1,398 | $444 | $37 | $124 | $358 |
| **$NF_3$ remote clean** | 14,427 | $117 | $234 | $17 | $334 |

[a] Break-even price calculated using a tax rate of 40% and discount rate of 10%.

As Table 12-5 shows, the high capital intensity of the abatement measures coupled with no annual benefits results in break-even prices that are all well above $100/$tCO_2e$. These significantly higher break-even prices suggest that achieving emission reductions in the PV manufacturing sector will require additional incentives or regulations to control F-GHG emissions.

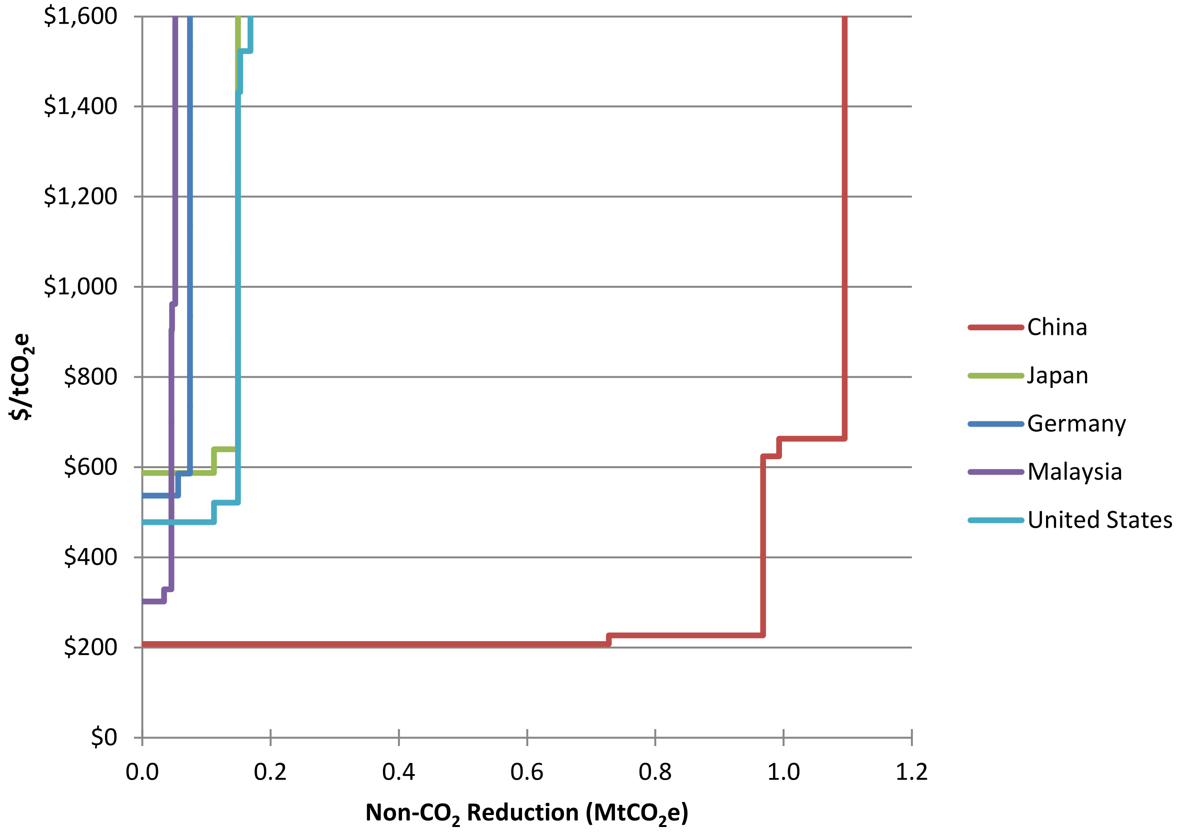
### IV.12.4.5 MAC Analysis Results

The global abatement potential for F-GHG reductions in the PV manufacturing sector is estimated to be 1.7 $MtCO_2e$, or 90% of total projected emissions in 2030. Table 12-6 presents the cumulative reductions achieved at selected break-even prices for the top five emitting countries and the grouping of countries that make up the rest of each region. Figure 12-4 shows the MAC curves for the top five emitting countries and the rest of world for this sector.

Table 12-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

| | Break Even Price ($\$/tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | −10 | −5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| China | — | — | — | — | — | — | — | — | — | — | **1.1** |
| Germany | — | — | — | — | — | — | — | — | — | — | **0.1** |
| Japan | — | — | — | — | — | — | — | — | — | — | **0.2** |
| Malaysia | — | — | — | — | — | — | — | — | — | — | **0.1** |
| United States | — | — | — | — | — | — | — | — | — | — | **0.2** |
| **Rest of Region** | | | | | | | | | | | |
| Africa | — | — | — | — | — | — | — | — | — | — | **0.0** |
| Central and South America | — | — | — | — | — | — | — | — | — | — | **—** |
| Middle East | — | — | — | — | — | — | — | — | — | — | **—** |
| Europe | — | — | — | — | — | — | — | — | — | — | **0.0** |
| Eurasia | — | — | — | — | — | — | — | — | — | — | **0.0** |
| Asia | — | — | — | — | — | — | — | — | — | — | **0.1** |
| North America | — | — | — | — | — | — | — | — | — | — | **—** |
| **World Total** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **1.7** |

**Figure 12-4: Marginal Abatement Cost Curves for Top Five Emitters and Rest of World in 2030**



As the results show, the abatement potential in the PV manufacturing sector can be significant. Unfortunately, these reductions in the absence of additional regulatory or market incentives would only be achievable at significantly high break-even prices (>$200/t$CO_2$e).

## IV.12.5 Uncertainties and Limitations

The PV industry is a relatively new manufacturing sector, with high levels of growth to meet continually growing demands for renewable energy. There is no comprehensive published information on the extent abatement systems are really in use in the industry. Assumed abatement system reduction efficiencies are really only achievable if the systems are properly operated and maintained, which may not always be the case (USEPA, 2008a and 2008b). Also, abatement system reduction efficiencies may vary by gas (e.g., $CF_4$ is harder to abate than other F-GHGs because of its thermo-stability). Additionally, there are not known voluntary reduction initiatives for the PV sector. Because of this the model facility is uncontrolled, information about the use of abatement in baseline emissions is highly uncertain.

Other reasons for uncertainties inherent to the baseline emission estimates include assumptions about the portion of the PV manufacturing industry that uses F-GHGs, and the unpredictability in the growth of the solar PV production capacity. The activity data used, the cumulative solar PV capacity, is modeled with its own set of assumptions from the IEA and is framed by the fast-growing renewable energy sector.

As this is the foundation of future baseline emission estimates, it gives rise to uncertainties. Furthermore, market dynamics will also contribute to the fluctuations with respect to facilities' utilization rates as well as fractions of PV cells started and inventoried, all of which are assumed constant for purposes of developing baseline emissions. Another limitation is that the baseline emission estimates do not take into account the retiring of PV cells. It is assumes that any new manufacturing is done to meet the increase in installed capacity and not to replace any replacement of capacity The emission estimates are hence conservative as inclusion of this assumption would lead to slightly higher emissions for each year. The use of Tier 1 emission factors to estimate emissions also gives rise uncertainty as it is the "least accurate estimation method" (IPCC, 2006). The Tier 1 method gives an aggregate emission estimate for all of the F-GHG using processes simultaneously, which introduces a higher level of uncertainty as the utilization rates of gases differ between etch and chamber cleaning processes.

Lastly, due to the similarities between this sector and the semiconductor manufacturing sector, the mitigation technologies considered for PV were those used in the semiconductor sector.

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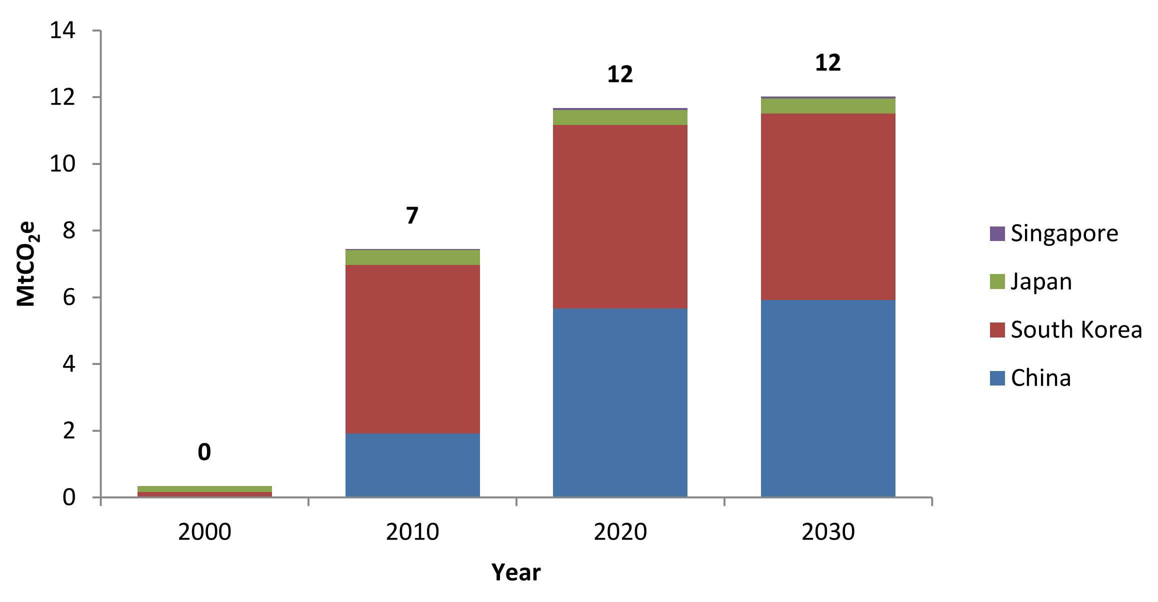
# IV.13. PFC Emissions from Flat Panel Display Manufacturing

## IV.13.1 Sector Summary

Flat panel display (FPD) manufacturing processes generate fluorinated greenhouse gas (F-GHG) emissions including sulfur hexafluoride ($SF_6$), nitrogen trifluoride ($NF_3$), and carbon tetrafluoride ($CF_4$), which are used in etching and chamber-cleaning processes commonly used in electronics manufacturing.

Global annual F-GHG emissions from FPD manufacturing are estimated to be approximately seven and a half million metric tons of carbon dioxide equivalents ($MtCO_2e$) in 2010, projected to grow to 12 $MtCO_2e$ by 2030.[1] Figure 13-1 shows the F-GHG emission projections by country from 2000 to 2030. The growth in emissions is primarily driven by projected growth in manufacturing capacity in China. The baseline projections presented here are updated relative to those presented in *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 to 2030* (USEPA, 2012). The updated projections include lower expected production levels of Liquid Crystal Displays and increased mitigation, resulting in significantly lower projected emissions. Emissions projections for this sector are particularly uncertain due to limited information on emissions rates and reduction efficiencies, variable industry production growth rates, and rapidly evolving FPD technologies.

**Figure 13-1: F-GHG Emissions from FPD Manufacturing: 2000–2030 ($MtCO_2e$)**



Source: U.S. Environmental Protection Agency (USEPA), 2012

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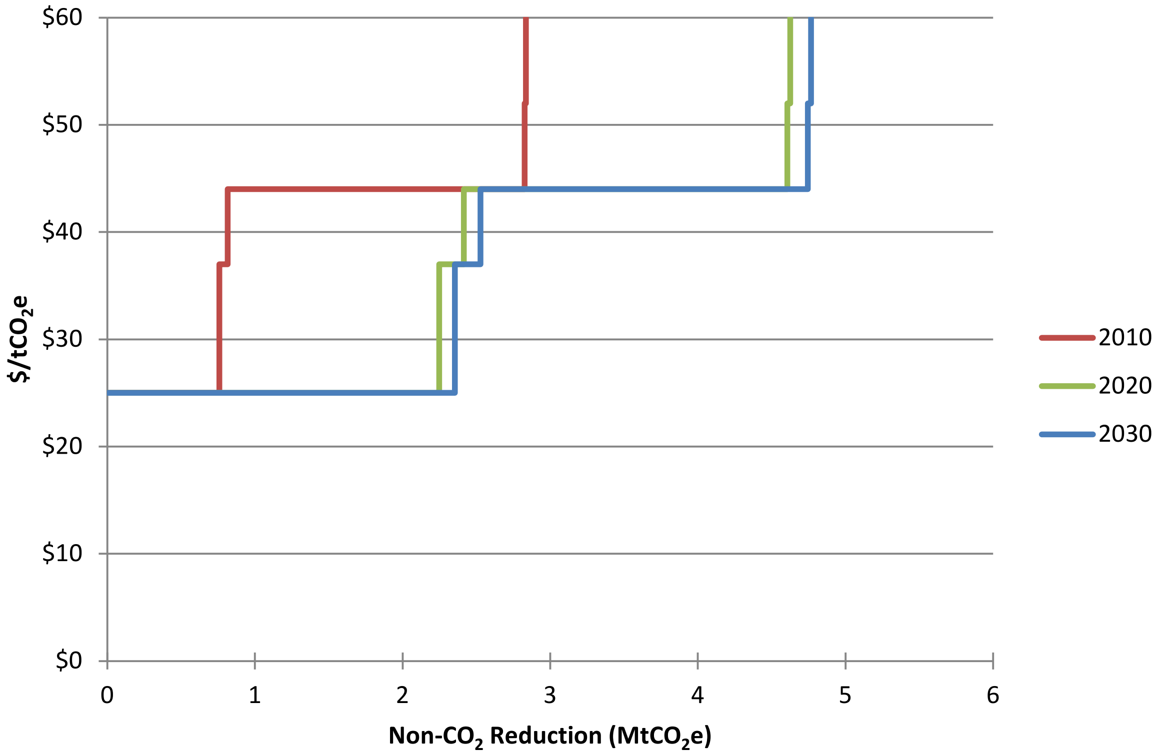
[1] The term flat panel display encompasses many technologies, such as liquid crystal displays, low temperature polysilicon (LTPS) or transparent amorphous oxide semiconductor (TAOS), and active matrix light emitting diodes (AMOLED). This analysis focuses on liquid crystal displays and does not include newer technologies such as AMOLEDs.

Six mitigation technology options were examined for this sector: central abatement, thermal abatement, catalytic abatement, plasma abatement, $NF_3$ remote chamber clean, and gas replacement.

Global abatement of F-GHG emissions in FPD manufacturing is estimated to be 9.3 $MtCO_2e$ in 2020 and 9.6 $MtCO_2e$ in 2030. The emissions reductions equate to 80% of the projected baseline emissions in each year. While all abatement options identified for this sector reduce emissions significantly, none has the ability to reduce or replace 100% of emissions from FPD manufacturing. Figure 13-2 presents the global MAC curves for 2010, 2020, and 2030 for the FPD manufacturing sector.

**Figure 13-2: Global Abatement Potential in FPD Manufacturing: 2010, 2020, and 2030**



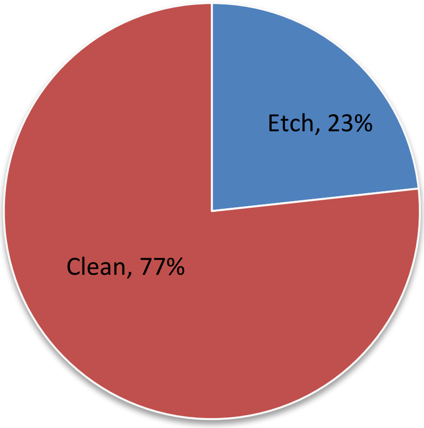
The following sections of this chapter first describe the activities and sources of F-GHG emissions in the FPD manufacturing sector and present the projected emissions for 2010 to 2030. Subsequent sections characterize the six abatement measures considered and present the engineering costs assumptions used in the MAC analysis. This is followed by a discussion of the MAC modeling assumptions used to estimate the global abatement potential. We conclude the chapter by presenting the MAC curves for each emitting country and briefly discuss some of the major uncertainties and limitations to our analysis.

## IV.13.2 Emissions from Flat Panel Display Manufacturing

In FPD manufacturing, high global warming potential (GWP) greenhouse gases are used for chemical vapor deposition (CVD) cleaning processes and plasma dry etching during the manufacture of arrays of thin-film transistors on glass substrates, which switch pixels of liquid crystal displays and organic light-emitting diode displays.

To evaluate the cost of reducing F-GHG emissions from FPD manufacturing, this analysis considers the emissions and reduction costs for a typical FPD manufacturing facility (manufacturing processes and uses of GHGs across the industry are generally similar), characterized based on an average gas consumption, an assumed 25 tools per facility with approximately 3.5 chambers each, and the average emissions of F-GHGs for etch and clean processes. Figure 13-3 shows the breakdown of etch and clean emissions for the typical facility.

**Figure 13-3: Global F-GHG Emissions in 2020 by Facility Type (% of GWP-Weighted Emissions)**



### IV.13.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

FPD facility-level emissions were modeled using estimated gas consumption data based on World LCD Industry Cooperation Committee (WLICC) reported data and Intergovernmental Panel on Climate Change (IPCC) Tier 2b emission factors. Because the WLICC does not fully represent all world manufacturing capacity, global emissions were estimated using estimated global capacity, in terms of area of substrate produced, from the DisplaySearch Equipment Database and IPCC Tier 1 emission factors for FPD manufacturing as opposed to using WLICC gas consumption information.

Global emission estimates take into account the WLICC goal, which was agreed to by all three member associations. The goal is to meet and maintain an aggregate 2010 F-GHG emission target of 10% of projected business-as-usual 2010 emissions, or 3.01 $MtCO_2e$ (expressed in the goal as 0.82 million tons of carbon equivalent). (This emission reduction goal was met in 2010; hence, mitigation technologies and strategies were assumed to have penetrated the market to a certain extent already in WLICC Partner countries Japan, Taiwan, and Korea.) The WLICC member associations are estimated to have 96% of the world's FPD manufacturing capacity in 2010. It is assumed, therefore, that there has already been some level of mitigation technology penetration to meet the stated goal in this sector in the baseline projections. Current market trends indicate major growth for capacity in this sector shifting to China, and without a reduction goal or mitigation measures, FPD emissions in China will drastically increase.

### IV.13.2.2 Emissions Estimates and Related Assumptions

The large majority of FPD manufacturing is in Asia, and production capacity continues to grow in that region. As shown in Table 13-1, from 2010 to 2030, emissions from global FPD manufacturing are expected to grow by a factor of 54 times, from 3 $MtCO_2e$ in 2010 to 162 $MtCO_2e$ in 2030. Much of this growth occurs between 2015 and 2030. This increase is expected to be attributed to growth in production and emissions in China for two reasons: (1) an expected increase in China's domestic demand for FPDs, and much of this demand will be met through domestic production (DisplaySearch, 2010); and (2) China's share of world emissions is projected to steeply increase partly because emissions for the WLICC member countries are assumed to meet and maintain the reduction goal of 3.01 $MtCO_2e$.

**Table 13-1: Projected Baseline Emissions from FPD Manufacturing: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR[a] (2010–2030) |
|---|---|---|---|---|---|---|
| China | 1.9 | 3.8 | 5.7 | 5.8 | 5.9 | 5.8% |
| South Korea | 5.1 | 5.4 | 5.5 | 5.6 | 5.6 | 0.5% |
| Japan | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.2% |
| Singapore | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 4.4% |
| **World Total** | **7.4** | **9.5** | **11.7** | **11.9** | **12.0** | **2.4%** |

[a] CAGR= Compound Annual Growth Rate

Source: USEPA, 2012

## IV.13.3 Abatement Measures and Engineering Cost Analysis

Six mitigation technology options were identified for the FPD manufacturing sector: central abatement, thermal abatement, catalytic abatement, plasma abatement, $NF_3$ remote chamber clean, and gas replacement.

- **Central abatement**: These are large-scale abatement systems that are generally located on the roof of facilities and are applicable to etch emissions ($SF_6$).
- **Thermal abatement**: These point-of-use (POU) abatement systems, that use heat to destroy or remove F-GHGs from effluent process streams, are connected directly to a manufacturing tool.
- **Catalytic abatement**: Tool effluent process streams are run through POU abatement systems with catalysts (e.g., CuO, ZnO, $Al_2O_3$) that destroy or remove F-GHGs.
- **Plasma abatement**: Plasma in a POU abatement system is used to react (destroy or remove) F-GHGs from the process effluent stream.
- **$NF_3$ remote chamber clean**: Highly ionized $NF_3$ is used to clean chemical vapor deposition chambers. This process is highly efficient (using ~98% of the gas in a process) resulting in lower emissions on a mass and $CO_2$ basis than traditional in-situ chamber clean processes which uses approximately 20% to 50% of the gas in a process (IPCC, 2006).
- **Gas replacement**: Higher GWP gases are replaced with lower GWP gases.

Table 13-2 presents the reduction efficiency and the applicability of each mitigation technology to emissions from a type of process (etch and/or clean). The next sections describe each of these mitigation options in more detail.

**Table 13-2: FPD Manufacturing Abatement Options**

| Abatement Option | Applicable Process Emissions Type(s) | Reduction Efficiency | Information Source |
|---|---|---|---|
| Central abatement | Etch | 77% | CDM project #3333 |
| Thermal abatement | Etch and clean | 95% | Fthenakis (2001), Beu (2005), and USEPA (2009) |
| Catalytic abatement | Etch and clean | 99% | Fthenakis (2001), Brown et al. (2012) |
| Plasma abatement | Etch | 97% | Fthenakis (2001), Hattori et al. (2006) |
| $NF_3$ remote chamber clean | Clean | 95% | Beu (2005) |
| Gas replacement | Clean | 77% | CDM methods NM0289, NM303, NM0317, NM0335 |

### IV.13.3.1 Central Abatement

Central abatement systems (CAS) have begun to be designed and used to handle the generally high gas ($SF_6$) flows used in FPD manufacturing because of the large size of the substrate being etched. A CAS is a large-scale thermal oxidation abatement system that is located on the roof of FPD facilities, so there are little expected space limitations for this technology. This technology has recently started to come online and is only applicable to etch emissions. Two CDM projects (one from LG and one from Samsung) in Korea have used this technology (CDM Project #3440 and CDM project #3333). Its use is, however, limited throughout the rest of the industry because it is expensive and relatively new.

The capital cost for a CAS is $4.5 million. The annual operation and maintenance (O&M) cost, which include items such as utilities and parts, is estimated to be $2.5 million for a facility. No revenues are generated from using a CAS.

### IV.13.3.2 Thermal Abatement

Thermal abatement systems can be used to abate emissions from both etching and CVD chamber-cleaning processes. The use of thermal abatement offers the benefit of not affecting the manufacturing process (Applied Materials, 1999); however, the systems do require space that may not be available in some facilities. In addition, these systems require large amounts of cooling water, and the use of the systems results in regulated $NO_x$ emissions.

The total facility capital cost for installing thermal abatement systems is estimated to be $5.7 million. This estimate includes costs for the systems, the necessary ducting, water recirculation and hook up, and natural gas costs (Fthenakis, 2001; Burton, 2003). The annual operating cost is estimated to be $328,860 at the facility level. No annual savings are associated with using this technology.

### IV.13.3.3 Catalytic Abatement

A catalytic abatement system is used to abate emissions from both etching and CVD chamber-cleaning processes. This type of abatement is applicable at most facilities, but again there may be some space constraints, as also discussed for thermal abatement systems, limiting the use of these systems in the market. Another limitation to their use is high catalyst replacement costs.

The capital cost associated with purchasing and installing the abatement systems is estimated to be $6.9 million per facility. To use catalytic abatement systems, facilities must factor in the annual cost of resources such as water, waste chemicals, electricity, and catalyst replacements. To cover these operating expenses, a facility manufacturing FPDs is estimated to incur an annual cost of $455,280. As with other abatement technologies considered in this sector, the use of thermal abatement systems will not result in annual savings.

### IV.13.3.4 Plasma Abatement

Plasma abatement systems are assumed to be applicable to etch processes in most facilities, with some physical space limitations. (These systems, however, are relatively smaller in size compared with thermal and catalytic systems.) Plasma abatement systems use a small plasma source that effectively dissociates the F-GHG molecules that react with fragments of the additive gas (hydrogen ($H_2$), oxygen ($O_2$), water ($H_2O$), or methane ($CH_4$)) to produce low molecular weight by-products such as hydrogen fluoride (HF) with little or no global warming potential (GWP). After disassociation, wet scrubbers can remove the molecules. The presence of additive gas is necessary to prevent later downstream reformation of F-GHG molecules (Motorola, 1998).

The capital cost for plasma abatement systems is estimated to be $1.8 million per facility (Fthenakis, 2001; Burton, 2003), which covers the purchase and installation of plasma systems. Plasma abatement systems require an annual operation cost of $1,190 per chamber, which includes general maintenance and use of the systems. The total annual facility cost is $51,850 based on an assumed number of tools per facility and chambers per tool. The use of plasma abatement systems will not result in annual cost savings.

### IV.13.3.5 $NF_3$ Remote Chamber Clean

$NF_3$ remote chamber clean is an alternative cleaning technology that has the benefit of having a particularly high utilization rate of $NF_3$ (~98%; IPCC, 2006), resulting in relatively low emissions compared with traditional chamber cleans. (Note: The stated utilization is based on utilizations for semiconductor manufacturing; as a result of large gas flows in FPD manufacturing the actual utilization may be lower.) $NF_3$ remote clean systems dissociate $NF_3$ using argon gas, converting the source gas to active F-atoms in the plasma, upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The by-products of remote clean include HF, fluorine ($F_2$), and other gases, most of which are removed by facility acid scrubber systems. The use of $NF_3$ remote clean systems is much more prevalent in new facilities because the technology was not available when many old facilities were constructed.

It is assumed that FPD facilities are not "$NF_3$ ready"; in other words, these facilities do not have the current infrastructure to handle the direct installation of $NF_3$ remote systems because this is a relatively new technology. Therefore, facilities incur capital costs, in addition to system costs, associated with items such as gas hook ups and necessary hardware such as manifolds and values. The facility cost is estimated to be $9.2 million. The annual facility cost for $NF_3$ remote clean is estimated to be $3.3 million (Burton, 2003). This cost is associated with the purchase of larger volumes of gas ($NF_3$ versus traditional chamber clean gases), general maintenance, and $F_2$ scrubs to remove the highly explosive gas from the effluent. No annual cost savings are associated with using this technology.

### IV.13.3.6 Gas Replacement

Gas replacement can be used to mitigate emissions from the traditional CVD chamber-cleaning process. Gas replacement can be applied in most facilities and has already been used throughout the industry in many instances. For this strategy, a lower GWP gas replaces a higher GWP gas. The most common replacement is using $NF_3$ to replace $SF_6$.

Facilities replacing $SF_6$ with $NF_3$ incur an estimated capital cost of $1.2 million for items such as gas hook ups and implementation. Annual savings for this option result from the lower cost of the replacement gas and were estimated to be $34,400, based on the incremental cost of the gases and the average amount of gas consumed per facility. Gas replacement has no operational costs.

### IV.13.3.7 Summary of Mitigation Technology Costs and Characteristics

Table 13-3 summarizes the information used to estimate the break-even prices discussed in the following section.

**Table 13-3: Engineering Cost Data on a Facility Basis**

| Abatement Option | Project Lifetime (Years) | Capital Costs (2010 USD) | Annual Revenue (2010 USD) | Annual O&M Costs (2010 USD) | Abatement Amount (tCOe) |
|---|---|---|---|---|---|
| Central abatement | 15 | $4,487,400 | $0 | $2,547,000 | 13,889 |
| Thermal abatement | 7 | $5,701,971 | $0 | $328,862 | 62,587 |
| Catalytic abatement | 7 | $6,906,594 | $0 | $455,277 | 65,222 |
| Plasma abatement | 7 | $1,814,664 | $0 | $51,847 | 14,941 |
| $NF_3$ remote clean | 21 | $9,200,867 | $0 | $3,374,861 | 56,496 |
| Gas replacement | 21 | $1,180,000 | $34,400 | $0 | 22,797 |

## IV.13.4 Marginal Abatement Costs Analysis

This section discusses the modeling approach and documents some additional assumptions used in the MAC analysis for the FPD manufacturing sector.

### IV.13.4.1 Methodological Approach

The MAC analysis applies the abatement measure costs discussed in the previous section at the model FPD manufacturing facility to calculate a break-even price for each abatement measure. This section presents how we defined the model facility used in this analysis and the technical effectiveness assumptions used to estimate the incremental reductions for each measure. This section also provides an example of how the break-even prices were calculated for each option.

### IV.13.4.2 Facility Definition

The typical facility considered in this analysis represents an average-sized FPD facility, with an estimated 25 tools and 3.5 chambers per tool. Based on WLICC-reported emissions data, the facility is assumed have an emissions breakdown of 23% etch emissions and 77% chamber clean emissions, which assumes a certain level of abatement is used. The facility emission breakdown is essential to this analysis, because some mitigation technologies are applicable to either both or just one type of manufacturing process (see Table 13-2 above).

### IV.13.4.3 Estimating the Technical Effectiveness Parameter

Similar to the methods employed for analyzing abatement in the semiconductor and photovoltaics manufacturing sectors, this analysis developed a technical effectiveness parameter, defined as the percentage reductions achievable by each technology/process combination. Estimating this parameter requires assumptions regarding the distribution of emissions by manufacturing process (etch and clean), in addition to process-specific assumptions on technical applicability and market penetration. These assumptions are held constant for all model years in the MAC analysis. Table 13-4 presents the technical applicability, market penetration, and reduction efficiency assumptions used to develop the abatement measures' technical effectiveness parameters.

**Table 13-4: Technical Effectiveness Summary**

| | Etch (23%) | | Clean (77%) | | | |
|---|---|---|---|---|---|---|
| Abatement Measure | Technical Applicability | Market Penetration | Technical Applicability | Market Penetration | Reduction Efficiency | Technical Effectiveness |
| Central abatement | 100% | 40% | 0% | n/a | 77% | **7%** |
| Thermal abatement | 85% | 30% | 85% | 55% | 95% | **40%** |
| Catalytic abatement | 85% | 10% | 85% | 15% | 99% | **12%** |
| Plasma abatement | 85% | 20% | 0% | n/a | 97% | **4%** |
| $NF_3$ remote clean | 0% | n/a | 100% | 20% | 95% | **15%** |
| Gas replacement | 0% | n/a | 50% | 10% | 77% | **3%** |

The technical effectiveness is a weighted average of the abatement measure's emissions reductions when applied to each applicable process(es). The share of total emissions attributed to each process (i.e., 23% etching and 77% cleaning) is the weight which is multiplied by the product of the technical applicability, market penetration, and reduction efficiency for each abatement measure. The technical effectiveness estimates are then multiplied by the facility annual emissions to estimate the abatement potential achievable through each of the six abatement measures. Summing the technical effectiveness across the six abatement measures yields the maximum level of emissions reductions that is technically achievable.

### IV.13.4.4 Estimating Break-Even Prices

The MAC model uses the estimated abatement project costs and benefits as described in Section 6.3 to calculate the break-even price for each abatement measure. Table 13-5 illustrates the break-even calculation for each abatement measure expressed in 2010 USD.

**Table 13-5: Example Break-Even Prices for Abatement Measures in FPD Manufacturing**

| Abatement Option | Reduced Emissions ($tCO_2e$) | Annualized Capital Costs ($\$/tCO_2e$) | Net Annual Cost ($\$/tCO_2e$) | Tax Benefit of Depreciation ($\$/tCO_2e$) | Break-Even Price ($\$/tCO_2e$) |
|---|---|---|---|---|---|
| Central Abatement System | 13,889 | $71 | $183 | $14 | $240 |
| Thermal abatement | 62,587 | $31 | $5 | $9 | $28 |
| Catalytic abatement | 65,222 | $36 | $7 | $10 | $33 |
| Plasma abatement | 14,941 | $42 | $7 | $12 | $37 |
| NF3 remote clean | 56,496 | $31 | $60 | $5 | $86 |
| Gas replacement | 22,797 | $10 | $0 | $2 | $8 |

As Table 13-5 shows, having no annual benefits and high initial capital costs results in relatively higher break-even prices. Break-even prices range between $8 and $240/$tCO_2$e based on the initial cost assumptions (unadjusted for country-specific prices). Gas replacement is the cheapest of the six options with a break-even price of $8/$tCO_2$e. The CAS is the most expensive at $240/$tCO_2$e. These costs are relatively high compared to some other sectors examined in this report, however they can be better understood in perspective of the high costs associated with this manufacturing industry. For example in 2004, Samsung and Sony invested more than $3 billion in capital costs for two new FPD production lines (Ramstad, 2011).

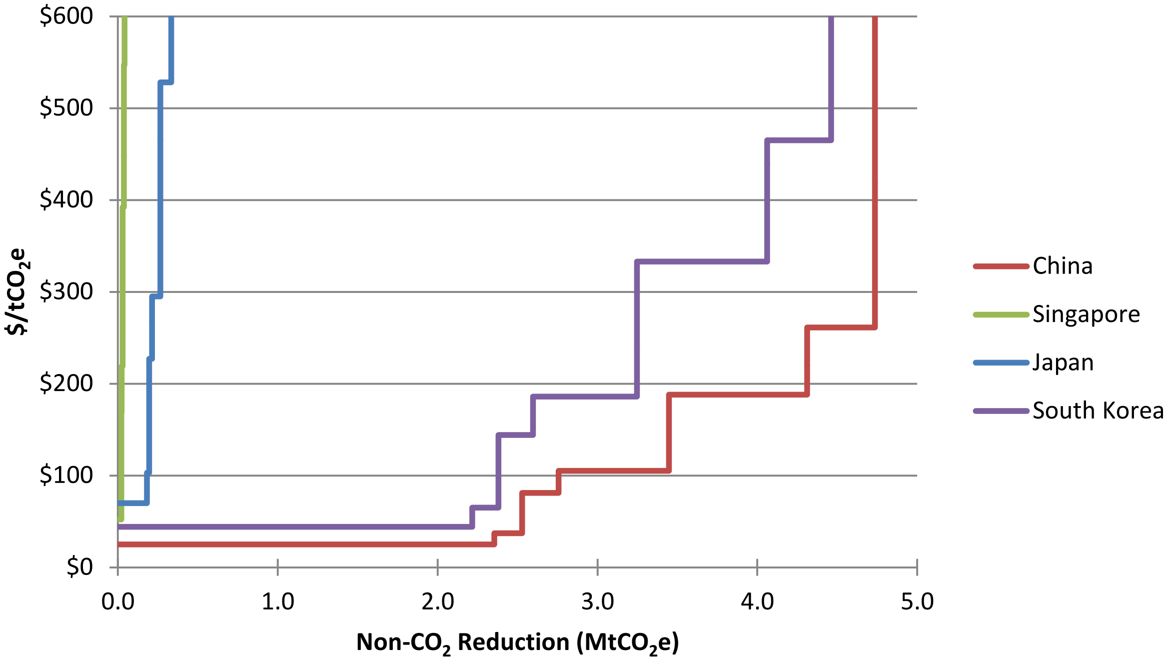
### IV.13.4.5 MAC Analysis Results

The global abatement potential for F-GHG emissions reductions in the FPD manufacturing sector is estimated to be 9.6 $MtCO_2e$, or 80% of total projected emissions in 2030. Table 13-6 presents the cumulative reductions achieved at selected break-even prices for China, Japan, Singapore, and South Korea. These are the only four countries with projected emissions in 2030 in the FPD manufacturing sector. Figure 13-4 presents the resulting MAC curves for each country in 2030.

**Table 13-6: Abatement Potential by Country/Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)**

| | Break-Even Price ($/$tCO_2e$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | −10 | −5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| China | — | — | — | — | — | — | — | 2.4 | 2.5 | 2.8 | 4.7 |
| Japan | — | — | — | — | — | — | — | — | — | 0.2 | 0.4 |
| Singapore | — | — | — | — | — | — | — | — | — | 0.0 | 0.0 |
| South Korea | — | — | — | — | — | — | — | — | 2.2 | 2.4 | 4.5 |
| **World Total** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **2.4** | **4.7** | **5.3** | **9.6** |

**Figure 13-4: Marginal Abatement Cost Curves by Emitting County in 2030**



As the results show, the abatement potential in the FPD manufacturing sector can be significant (80% of sectoral emissions). Over 2.4 $MtCO_2e$ of F-GHG emissions could be reduced in China at a carbon price of ~\$25/$tCO_2e$; these reductions alone represent 20% of global emissions in 2030.

## IV.13.5 Uncertainties and Limitations

Because of the similarities between this sector and the semiconductor manufacturing sector, most mitigation technologies (and hence cost estimates) are assumed to be the same as for the semiconductor manufacturing sector (with the exception of the CAS technology). We made this assumption because of the limited amount of public information on the extent to which various types of mitigation technologies are being used in this sector.

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