

Technical Evaluation
of the Emissions and
Control Costs of
High Global Warming
Potential Gases.



**Minnesota
Pollution
Control
Agency**

Prepared by: Minnesota Pollution Control Agency
Environmental Analysis and Outcomes Division
Air Policy and Mobile Sources Unit
Climate Change Program
Saint Paul, Minnesota, 55155

MPCA Staff Jim Sullivan
Contacts: (651) 757-2769
 Barbara Conti
 (651) 757-2288

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Executive Summary

The Minnesota Pollution Control Agency has prepared a report for the Minnesota Legislature that identifies the various sources, uses and control technologies for gases with high global warming potentials released in the state of Minnesota. The report was specifically developed to comply with Minn. Stat. §216H, and provides information that can be used to further implement the greenhouse gas targets and deadlines identified in the Next Generation Energy Act. Information used to develop the evaluation included similar evaluations published by other public-sector entities, specialty literature, discussions with industry representatives and data submitted on the purchase of high global warming potential gases under Minn. Stat. §216H. The information included emissions and cost effectiveness data. This report recommends a rule scoping process on high-global warming potential gases that will be used to better identify the manner in which to collect emission data, the role of voluntary programs in reducing emissions of high global warming potential gases and the role of greenhouse gas emission reporting in a broader greenhouse gas reporting strategy.

Introduction

The Minnesota Pollution Control Agency (MPCA) was directed to generate a report on the use, emission sources, alternatives and cost effectiveness of control options for high global warming potential (GWP) gases in Minnesota that is consistent with the following requirements (Minn. Stat. §216H):

By February 1, 2009, the commissioner of the Pollution Control Agency shall submit a report to the chairs and ranking minority members of the senate and house of representatives committees with primary jurisdiction over environmental policy that identifies the uses and emissions sources of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride in this state and suggests options for reducing or eliminating those uses and emissions and the costs of implementing those options. The options for reducing emissions must include phasing out specific consumer products containing high global warming potential gases where that is cost-effective.

This report is an important step in developing and implementing a statewide greenhouse gas reduction strategy, consistent with the targets identified in the 2007 Next Generation Energy Act (Act). The Act included requirements for Minnesotans to increase energy efficiency, expand community-based energy development, and establish a statewide goal to reduce greenhouse gas (GHG) emissions. The act established aggressive goals for Minnesotans to reduce statewide GHG emissions across all sectors:

- 15% below 2005 levels by 2015
- 30% below 2005 levels by 2025
- 80% below 2005 levels by 2050

Gases with high global warming potentials (high-GWPs) comprise approximately two percent of the annual statewide emissions budget (See Figure #1), consistent with a national emission inventory. The Minnesota Climate Change Advisory Group (MCCAG) climate change action plan noted that “Industrial process emissions accounted for about 1% of the state’s greenhouse gas emissions in 2005, and these emissions are rising due to the increasing use of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) as substitutes for ozone-depleting

chlorofluorocarbons (CFCs).”ⁱ The contributions of greenhouse gases by economic sector in Minnesota are presented in Figure #1 and were adapted from the MCCAG Climate Change Action Plan. The emissions from industrial processes comprise the emissions of high-GWP gases. Emissions of HFCs from automobile air conditioning units and sulfur hexafluoride (SF₆) emissions from the utility sector increase the percentage of high-GWP emissions in Minnesota to approximately two percent of the statewide annual emissions of greenhouse gases.

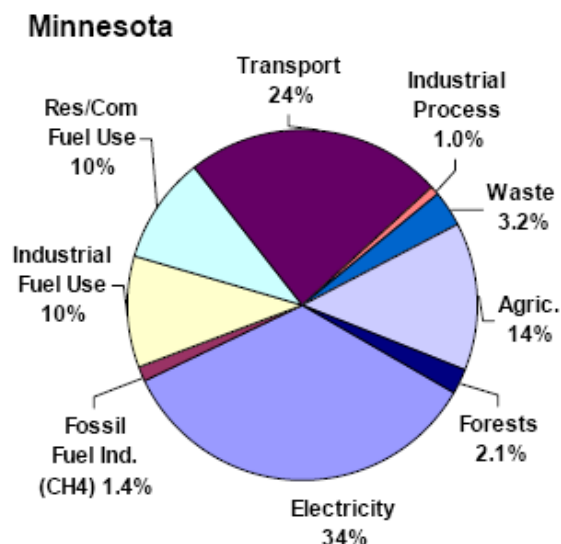
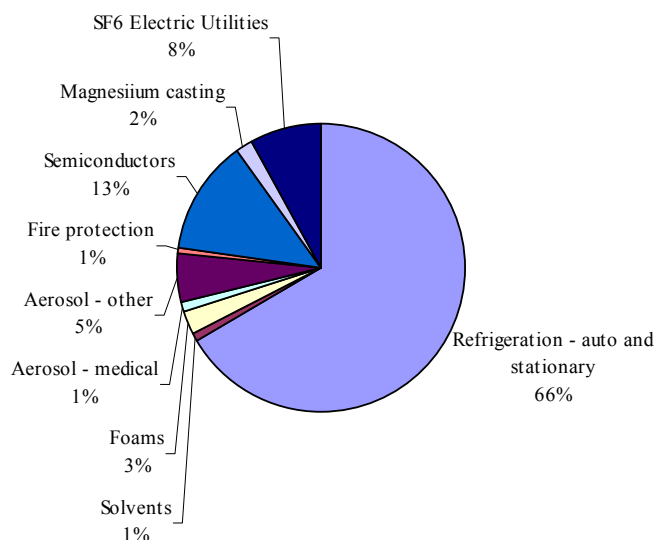


Figure #1 – Annual Contributions (percentage) of Greenhouse Gases by Economic Sector in Minnesota.

Figure #2 - HGWP Gases National Distribution (by CO₂eq) 2010



ⁱ Minnesota Climate Change Advisory Group, 2008. Final Report. A Report to the Minnesota Legislature. Saint Paul, MN. EX-2.

This percentage equates to approximately 3 million tons of carbon dioxide equivalent emitted annually. The distribution of contributions of high-GWP gases in Minnesota is likely to be similar to the national emission profile (See Figure #2). While high-GWP gas emissions may be small, they are typically emissions where control technologies or substitute gases exist. Reducing high-GWP gas emissions from the annual statewide emissions budget is a step in attaining the statewide emission reduction goals under the Next Generation Energy Act.

The MCCAG offered a three-pronged policy design to address the development of a long-term emission control strategy for high-GWP gases:

- Elimination of emissions of high-GWP greenhouse gases (GHGs) at reasonable cost;
- Promotion and funding for process optimization; and,
- Use of lower-impact alternatives for coolants, refrigerants, aerosols, solvents, and insulation.

To implement the policy directions identified above, the MCCAG identified the following mechanisms:

- MPCA rulemaking process for a comprehensive GHG reporting strategy that includes high-GWP gases;
- Legislative action to provide tax incentives and funding for technical support and assistance; and,
- Technical support through the Minnesota Technical Assistance Program (MnTAP) or similar entities.

Based on the MCCAG evaluation, many of the sectors appear to be able to reduce emissions within a \$15 per ton carbon dioxide equivalent control cost. The MCCAG considered this value to be a reasonable cost. After reviewing the technical and administrative data on the high-GWPP reporting, the MPCA developed two specific recommendations based on the sector review and the MCCAG Climate Change Action Plan. The MPCA's specific recommendations for future high-GWP gas activities are provided at the end of his Report.

Scope of the Report

This report is a summary of the MPCA technical evaluation on control effectiveness and cost conducted for each economic sector where high-GWP gases are used. The sectors include refrigeration and cooling, foam blowing industries, fire suppression, semiconductor manufacturing, magnesium casting electrical generation and transmission, and specific consumer products. The results of this analysis are found in the MPCA *Technical Evaluation on the Emissions and Control Costs of High Global Warming Potential Gases* (Technical Report), developed in conjunction with this report. A copy of the Technical Report is available for review and can be found on the MPCA website.

Sources of Information

The information used in this Report was obtained from the following sources:

- Review of existing high-GWP reports compiled by various public sector entities;
- Review of available specialty literature;

- Case study data; and,
- 2007 MPCA high-GWP chemical purchase and manufacturer reporting data.

The information developed from existing high-GWP reports was reviewed for analytical methodology, and relevance to industry in Minnesota. Many of the reports used in this analysis were developed to assess national and international emissions. While the specific emission inventories may not directly reflect the Minnesota situation, control technologies and costs are considered to be relevant and applicable to industry in Minnesota. Specialty literature was used where information was lacking or found to be out of date.

The MPCA attempted to use the high-GWP reporting data collected for the 2007 reporting season, pursuant to Minn. Stat. §216H.11. The modest response rate limited the MPCA's use of this data in the Report. For further discussion on reporting response rate, see the discussion in the *Program Administration Evaluation* in this report.

The foundation for the MPCA Report is the 2001 Environmental Protection Agency (EPA) *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions* and the EPA 2006 *Global Mitigation of Non-CO₂ Greenhouse Gas* report. The EPA reports presented the following data for each high-GWP emission sector:

- Baseline emissions of high-GWP gases. The source of the emissions in the United States was summarized, followed by a baseline forecast of U.S. emissions from that source through 2020.
- This baseline was estimated under a “no-action” case scenario and, for some sectors, a “voluntary technology adoption” scenario where active industry efforts existed.
- High-GWP gas emission reduction options and associated costs.

The MPCA used this presentation format throughout the various sectors analyzed. Since few voluntary efforts appear to exist in Minnesota, the MPCA used the “no action” baseline to predict future emissions. Other bodies of information, including peer-reviewed and professional specialty literature, were employed to augment and update various features of the EPA analysis. The data and information used in this report was evaluated to determine that it accurately and credibly reflected the uses of high-GWP gases in the various sectors in Minnesota.

The Technical Report is composed of 10 chapters. Chapter 1 is an introduction to the issues presented through the legislation and an overview of climate change and engineered gases. The work presented in Chapter 2 is a review of previous and existing policy and regulatory approaches from Minnesota, other states, federal activities and international efforts. The analytical approach to the project is described in Chapter 3. Chapters 4 through 9 are a review of each sector that may potentially be affected by a high-GWP program. This analysis includes the costs associated with emission control or elimination.

Discussion of Findings

The MPCA reviewed the various high-GWP gas emission control strategies and cost estimates for selected economic sectors where these gases are used. In addition, the MPCA reviewed the implementation of the statutory reporting requirements for the purchase and manufacture of high-GWP gases.

Technical Evaluation

The MPCA recommendations are guided in part by recommendations from the MCCAG. The MCCAG policy direction for this report was the elimination of high-GWP emissions at a reasonable cost. The MCCAG stated that “For purposes solely of calculation of the costs and effects of this recommendation, a reasonable cost is determined to be \$15 per ton CO₂ equivalent.” The MPCA notes that many of the sectors reviewed may be able to reduce emissions within the \$15 per ton cost criteria. The information provided below is a review of the predicted national baseline data by sector, the potential reductions that are achievable using the \$15 control price, and the percent reduction if control technology is adopted. This information is presented for the years 2010 and 2020.

Table #1 - National Emission Reduction and Cost Analysis using a \$15/tCO₂e Control cost (EPA, 2006).

Sector	2010 Baseline (MtCO ₂ eq) ^d	2010 a Reduction (\$15/tCO ₂ e) ^d	2010 b Reduction (%)	2020 Baseline (MtCO ₂ eq)	2020 a Reduction (\$15/tCO ₂ e)	2020 b Reduction (%)	Options/Comments
Refrigeration (auto and stationary)	148	11.5	7.8	264	78	29.5	Least cost are leak repair for large system, recovery for small system and enhanced HFC-134a system for mobile air conditioning.
Solvent	1.7	0.43	25.3	2	1.05	52.5	Substitution and improved system design
Foams	5.7	0.2	3.5	11.3	1.17	10.4	Substitution
Aerosol - medical	2.7	0	0	5.5	0	0	No effective substitutes
Aerosol - other	12.1	4.67	38.6	14.8	8.43	57.0	Assumes no effective voluntary program – “no action” baseline
Fire protection	1.6	0	0.0	1.9	0	0.0	Long life of installed system - replacements being developed
Semiconductors	28.2	20.0	70.9	46.1	32.7	70.9	Assumes “no action” baseline
Magnesium Casting	4.6	4.5	97.8	6.4	6.26	97.8	There is an IMA goal to phase out by 2011 but participation in MN is not known - assumed "no action" baseline
Electrical Utilities SF ₆	17.6	10.05	57.1	18.9	10.78	57.0	Assumes “no action” baseline
Total	222.2	51.35	23.1 c	370.9	138.39	37.3 c	

a This column represents the amount removed by sector at a cost of \$15 per ton of carbon dioxide equivalent.

b This column represents the percentage of pollutants removed, by sector, from the overall baseline for 2010 and 2020.

- c The value in the shaded area represents the overall percentage of pollutants removed from all sectors in comparison to the baseline for 2010 and 2020.
- d Million ton of carbon dioxide equivalent (MtCO₂eq) – Dollars per ton of carbon dioxide equivalent (\$/tCO₂e).

Program Administration Evaluation

The MPCA implemented the manufacturer and purchaser reporting requirements through a combination of a mass mailing and email effort. On September 8, 2008, the MPCA sent a total of 3,260 letters informing permittees and other likely businesses of the new reporting requirement. In addition, notice was provided in the State Register on September 15, 2008, along with an email to members of the MPCA Listserve, comprised of members of the public interested in the topic of air quality and climate change. The letter provided information on the nature of the reporting requirements, thresholds for reporting and a link to the MPCA website for additional information. The MPCA high-GWP website provides information on the requirements of the statute, reporting forms and supporting data.

The MPCA high-GWP reporting data for 2007, required by Minn. Stat. §216H.11, is presented in Table #2. Of the 3,260 letters sent by MPCA, a total of 279 letters were returned as undeliverable. Our overall response rate for this effort was less than 2%, restricting the inferential value of the data for this report. The following table is a breakdown of the reporting results:

Table #2 – High-GWP Reporting Response by Sector

Sector	Number of Reports Submitted	Approximate size of the sector
HVAC/Refrigeration	32	>5,000
Utilities	5	<200
Semiconductor	5	6
Fire Suppression	1	20,000
Consumer product	2	Not known at this time.
Foam Blowing Agent	1	52
Magnesium casting	1	20
Other	1	*
Manufacturers of high-GWP gases	5	30
Total Reports	53	

* This category represents to use of a high-GWP gas that does not fit into a specific sector category.

The low response rate is likely a function of three factors: the data collection method, including the content of the MPCA letter; the limited time available to build industry cooperation; and the 500 metric ton carbon dioxide equivalent reporting threshold.

The language of the statute required purchasers of high-GWP gases that exceeded 500 metric tons carbon dioxide equivalent to report the purchase and to describe the use. The statute did not describe or define the scope of a purchaser for purposes of reporting under the statute. The MPCA designed the reporting program to address end-users of high-GWP gases. In an effort to minimize or eliminate double-counting, the MPCA requested that if a contractor or service provider managed high-GWP gases for a company, then the vendor or service provider should submit the report on behalf of their client. This approach was primarily designed to facilitate reporting in the refrigeration and heating/cooling sector, with recognition that other sectors may operate in a similar fashion. This practice was unsuccessful. Very few contractors provided a report. Those that submitted a report did so only for their own purchases and did not provide end

use destination information. Several contractors contacted the MPCA and indicated that they were not willing to report as doing so would make their client list public, thereby revealing their client base to competitors. The Minnesota Data Practices Act does not provide protection to client lists.

Several chain restaurants indicated that while they owned many of their facilities, gas purchases varied from a central operations center to individual contracts with a local service provider. As a result, they felt that each of their individual operations would not result in a 500 metric ton carbon dioxide equivalent purchase and would not submit a company-wide report. Enforcing the statute under this situation presented a difficult challenge in part due to the imprecise nature of the definition of a purchaser under the statute.

There are two elements of the statute that if met, require a regulated party to submit a report. The first is the purchase of a high-GWP gas that exceeds 500 metric tons of carbon dioxide equivalent. The challenges of applying this threshold to purchasers in Minnesota were presented above. The second element is the “point of sale” aspect of a purchase under the statute. In order to be subject to reporting under the statute, a purchase of a high-GWP gas must be made in Minnesota. A number of companies contacted the MPCA and noted that while they had purchased gas quantities that exceeded 500 metric tons of carbon dioxide equivalent, their service provider, contractor or corporate operations center purchased the gas outside of Minnesota. As many of the service providers, contractors, or corporations did not make any purchase of high-GWP gases within the state of Minnesota, there was no legal obligation for them to make a report for themselves or their Minnesota clients. Enforcement under these circumstances would have been difficult and resource intensive.

Conducting a rule scoping process would greatly facilitate this effort to clarify the universe of entities required to report and information required to build a credible dataset. The recommended rule scoping process would allow the MPCA to better understand the purchaser/end user relationship and develop a more precise definition of purchaser consistent with the statute and industry practice, thereby enhancing reporting efficiency and enforceability.

Finally, there was insufficient time between the effective date of the statute and the reporting deadline to develop the sector-specific parameters that make for a successful emission reporting program. The initial short reporting window affected our ability to create effective links with the association and trade organizations within this diverse collection of sectors. The ability to meet with trade associations was considered paramount in light of the low reporting threshold (500 metric tons – carbon dioxide equivalent) and the relationship between purchases of high-GWP gases and emissions and the diversity of operating scenarios.

The data reviewed in the development of the Technical Report indicates that the use of high-GWP gases in Minnesota presents challenges for control and substitution along with some opportunities for innovation. For some sectors, a substitute gas is not available. For other sectors, high-GWP gases are integral to the manufacturing process. Consumer products that contain potential emissions of high-GWP gases (e.g., aerosols) are not a substantial component of the state’s GHG emission inventory. California has initiated a review of aerosol “dusters” (e.g., cans of “air” used to clean computers) which may lead to a ban in that state. The MPCA does not yet have sufficient knowledge of the issues involved with “dusters” and their use in Minnesota. Based on MPCA’s review of high-GWP gas bans by other states, the MPCA does

not see opportunities for significant reductions in high-GWP gas emissions in Minnesota resulting from a specific ban at this time.

The MPCA also implemented the mobile air conditioner (MAC) leak rate statute (Minn. Stat. §216H.12). The language of the mobile air conditioner leakage report is presented as follows:

Minn. Stat. §216H.12 - Mobile Air Conditioner Leakage Rates

Subdivision 1. Leakage disclosure. Beginning January 1, 2009, a manufacturer selling or offering for sale a new motor vehicle in this state containing a mobile air conditioner that uses the high-GWP greenhouse gas HFC-134a (1,1,1,2-tetrafluoroethane) as a refrigerant must, 90 days prior to the initial sale or offer for sale, report to the commissioner the leakage rate, in grams of refrigerant per year, for the type of mobile air conditioner contained in that make, model, and model year. The leakage rate must be calculated using the information provided in the most recently published version of the SAE International document J2727, "HFC-134a Mobile Air Conditioning System Emission Chart." The method by which the leakage rate is calculated, accounting for each component of the air conditioning unit, must also be reported to the commissioner.

Subd. 2. Posting. Beginning January 1, 2009, the agency and the Office of the Attorney General must post on their Web sites:

- (1) the leakage rate disclosed by a manufacturer under subdivision 1 for each model and make of new motor vehicle sold or offered for sale in this state; and,
- (2) the following statement: "Vehicle air conditioning systems may leak refrigerants. Information provided in the chart compares the potential global warming effects of refrigerant leakage from different makes and models of vehicles."

To notify automobile manufacturers of Minnesota's new reporting requirement, two outreach efforts were made. One letter was a traditional mailing that was sent to manufacturer's environmental staff, as identified through the Interstate Mercury Education and Reduction Clearinghouse. The second notification was sent by electronic mail (email) to interested parties who are members of the Association of International Automobile Manufacturers and/or the Auto Alliance.

The report form was included in the email and was also available on the MPCA's web site. A new web page was posted specifically for the MAC program. Reports for over 360 makes and models from 17 manufacturers were submitted. A small number of manufacturers have no direct sales in Minnesota and do not report. MPCA staff compiled the reported data in a spreadsheet which was posted on the MPCA's MAC program web site and the Minnesota Attorney General's web site in December, 2008. Updates for newly-released vehicle models or changes to existing vehicle data will be made periodically, most likely on a quarterly basis. Information from this data collection effort was used in the Technical Report.

Recommendations

The MPCA offers the following two specific recommendations based on the sector review and the MCCAG Climate Change Action Plan:

Recommendation #1

The MPCA recommends that a rule scoping process be conducted to develop a rule to reduce high-GWP emissions through reasonable cost efforts. As noted in the sector evaluations, many of the sectors appear to be able to reduce emissions within a \$15 a ton carbon dioxide equivalent control cost. A rule scoping process would provide for greater resolution of the sector-specific operations that could lead to more cost-effective regulation and could commence in 2009 with completion in 2011. This process would include consideration of appropriate product bans.

Within the rule-scoping process, the MPCA would also be able to determine the role of a voluntary emissions reduction program in an overall statewide strategy of high-GWP emission reduction. Several voluntary industry and EPA-sponsored programs exist; however, most Minnesota companies are not currently participating. The rule scoping process would be useful in determining the opportunities for volunteer emission reduction program membership based on potential emission control technology and substitutes.

Recommendation #2

The MPCA recommends that the current high-GWP reporting scheme be converted to an emission-based program, along with an increase in the mandatory reporting threshold. The rationale for this approach is based on the nature of high-GWP gas usage and purchase behavior. The purchase of high-GWP gases is not a robust surrogate for determination of annual emissions for comparison to the targets in the Next Generation Energy Act. The use of high-GWP gas purchases as a means to evaluate emissions is imprecise, in part because of the lack of alignment between purchase and gas usage within the state. As noted above, the purchase of high-GWP gases must be made within the state and above the specific reporting threshold in order to be subject to reporting. Many large high-GWP gas consumers purchase their high-GWP commodities outside the state, thereby eliminating the need to report.

The emission reporting threshold should be increased to a value consistent with programs in other states and countries. Thresholds in other states range between 2,500 and 100,000 tons of carbon dioxide equivalent, with most states pursuing thresholds in the range of 10,000 tons. The rationale for this value is based on the administrative burden placed on smaller generators of high-GWP emissions with respect to cost and the need to focus regulatory resources on facilities that are high-volume emitters of high-GWP gases. Minnesota is one of the few states that specifies a high-GWP reporting threshold rather than an aggregate of all climate change gases (i.e., combination of CO₂ and non-CO₂ gases). A long-term goal of the Next Generation Energy Act is to reduce GHG emissions consistent with specific statutory targets and deadlines. Emission reporting is the manner in which statewide performance is evaluated with these expectations. Shifting the focus from high-GWP purchases to a facility-specific emission reporting requirement would further the implementation of the Next generation Energy Act.

The development of an emission reporting scheme would be best served through the rule scoping process. A rule scoping process would allow the MPCA to better identify participants, basic data elements (including reporting thresholds), reporting frequency, *di minimis* values and the scope of reporting (e.g., sectors, direct and indirect emissions). The reporting process should also harmonize the high-GWP activities with other climate change activities proposed by MCCAG including greenhouse gas reporting.

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1.0 Introduction

This legislative report (herein referred to as “Report”) describes the various emission sources and control options of high global warming potential gases (High-GWP gases) in the state of Minnesota. It also provides information related to cost of control and recommendations on further actions. The Report also summarizes purchases of high-GWP gases as reported under Minn. Stat. §216H.11.

The Report is composed of 10 chapters. Chapter 1 is an introduction to the issues presented through the legislation and an overview of climate change and engineered gases. The work presented in Chapter 2 is a review of previous and existing policy and regulatory approaches from Minnesota, other states, federal activities and international efforts. The analytical approach to the project is described in Chapter 3. Chapters 4 through 9 are a review of each sector that may potentially be affected by a high-GWP program. This analysis includes the costs associated with emission control or elimination. The final chapter of this Report describes the MPCA recommendations that result from the review of the issues presented in this report.

1.1 Background

There are three distinct authorities that shape current Minnesota climate change activities: the Next Generation Energy Initiative (NGEI); the Next Generation Energy Act (NGEA); and the 2008 Energy Omnibus Bill. The NGEI is an Executive policy initiative through the Governor’s office, designed to provide direction on addressing the issue of climate change and energy. The NGEA is a law enacted in 2007 that identifies specific objectives and resources to address the issue of climate change in Minnesota. Lastly, the 2008 Energy Omnibus Bill is a law that was passed in furtherance of the NGEI and NGEA. It is the 2008 Energy Omnibus Bill that authorized the creation of this Report. The following is an overview of each action and the relevance of each authority to the issue of high-GWP gases.

1.1.1 Next Generation Energy Initiative

On December 12, 2006, Minnesota Governor Tim Pawlenty announced the state’s Next Generation Energy Initiative (NGEI), including the “development of a comprehensive plan to reduce Minnesota’s emissions of greenhouse gas emissions.” In this announcement, the Governor requested assistance from the Center for Climate Strategies (CCS) in the development of a Minnesota Climate Mitigation Action Plan (Action Plan) and formation of the Minnesota Climate Change Advisory Group (MCCAG). The MCCAG was charged with developing a comprehensive set of state-level policy recommendations to the Governor through a stakeholder-based consensus building process that was facilitated by CCS in coordination with the Minnesota Department of Commerce (DOC) and Minnesota Pollution Control Agency (PCA). The NGEI was responsible for the development of the Minnesota Climate Mitigation Action Plan through the MCCAG process. The MCCAG work included:

- Development, prioritization, analysis, and approval of a final collection of existing and proposed actions that could contribute to GHG emissions reductions;
- Review and approval of an inventory of historical and forecasted GHG emissions in Minnesota as a basis against which to gauge priorities and progress; and
- Consideration of costs and benefits of recommended options.

The NGEI directed that the Action Plan be delivered to the Governor and the Legislature in February of 2008. The Action Plan contains 46 policy recommendations organized into six categories:

- Energy Supply Policy (ES)
- Residential, Commercial, and Industrial Policy (RCI)
- Transportation and Land Use Policy (TLU)
- Agriculture, Forestry, and Waste Management Policy (AFWM)
- Cap-and-Trade (C&T) Policy
- Cross-Cutting Issues Policy (CC) Recommendations.

The policy recommendations address a wide range of activities including actions to address the reduction of high global warming potential gases. The most relevant policy recommendation addressed by this Report is RCI-5 “Program to reduce Emissions of NonFuel, High Global Warming Gases.”

In the MCCAG Action Plan, it was noted that “Industrial process emissions accounted for about 1% of the state’s greenhouse gas emissions in 2005, and these emissions are rising due to the increasing use of hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) as substitutes for ozone-depleting chlorofluorocarbons (CFCs).”¹ This percentage equates to approximately 1.5 million tons of carbon dioxide equivalent emitted annually.

1.1.2 Next Generation Energy Act

The Next Generation Energy Act of 2007 included requirements for Minnesotans to increase energy efficiency, expand community-based energy development, and establish a statewide goal to reduce greenhouse gas (GHG) emissions. The act established aggressive goals for Minnesotans to reduce statewide GHG emissions across all sectors:

- 15% below 2005 levels by 2015
- 30% below 2005 levels by 2025
- 80% below 2005 levels by 2050

1.1.3 2008 Energy Omnibus Bill

The 2008 Energy Omnibus Bill in part directed the MPCA to collect data on the sale, purchase and use of high-GWPs in Minnesota (Minn. Stat. §216H.11) and the leakage rates of HFC-134a from mobile air conditioners (Stat. §216H.12). In addition, the 2008 Energy Omnibus Bill contained a requirement for a legislative report on the control options available for users of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆) (Minn. Stat. §216H). The language of the statute provided the following direction to the MPCA on the collection of manufacturer and purchaser data:

Minn. Stat. §216H.11 High-GWP Greenhouse Gas Reporting
Subdivision 1. Gas manufacturers. Beginning October 1, 2008, and each year thereafter, a manufacturer of a high-GWP greenhouse gas must report to the agency the total amount of each high-GWP greenhouse gas sold to a purchaser in this state during the previous year.

Subd. 2. Purchases. Beginning October 1, 2008, and each year thereafter, a person in this state who purchases 500 metric tons or more carbon dioxide equivalent of a high-GWP greenhouse gas must report to the agency, on a form prescribed by the commissioner, the total amount of each high-GWP greenhouse

gas purchased during the previous year and the purpose for which the gas was used.

Subd. 3. Acceptance of federal filing. With the approval of the commissioner, this section may be satisfied by filing with the commissioner a copy of a greenhouse gas emissions report filed with a federal agency.

The MPCA implemented the manufacturer and purchaser reporting requirements through a combination of a mass mailing and email effort. On September 8, 2008, the MPCA sent a total of 3,260 letters informing permittees and other likely businesses of the new reporting requirement. In addition, notice was provided in the State Register on September 15, 2008, along with an email to members of the MPCA Listserve, comprised of members of the public interested in the topic of air quality and climate change. The letter provided information on the nature of the reporting requirements, thresholds for reporting and a link to the MPCA website for additional information including reporting forms. The MPCA also established a website explaining the requirements of the statute and containing relevant reporting form and supporting data.

The language of the mobile air conditioner leakage report is presented as follows:

Minn. Stat. §216H.12 - Mobile Air Conditioner Leakage Rates

Subdivision 1. Leakage disclosure. Beginning January 1, 2009, a manufacturer selling or offering for sale a new motor vehicle in this state containing a mobile air conditioner that uses the high-GWP greenhouse gas HFC-134a (1,1,1,2-tetrafluoroethane) as a refrigerant must, 90 days prior to the initial sale or offer for sale, report to the commissioner the leakage rate, in grams of refrigerant per year, for the type of mobile air conditioner contained in that make, model, and model year. The leakage rate must be calculated using the information provided in the most recently published version of the SAE International document J2727, "HFC-134a Mobile Air Conditioning System Emission Chart." The method by which the leakage rate is calculated, accounting for each component of the air conditioning unit, must also be reported to the commissioner.

Subd. 2. Posting. Beginning January 1, 2009, the agency and the Office of the Attorney General must post on their Web sites:

- (1) the leakage rate disclosed by a manufacturer under subdivision 1 for each model and make of new motor vehicle sold or offered for sale in this state; and,
- (2) the following statement: "Vehicle air conditioning systems may leak refrigerants. Information provided in the chart compares the potential global warming effects of refrigerant leakage from different makes and models of vehicles."

To notify automobile manufacturers of Minnesota's new reporting requirement, two outreach efforts were made. One letter was a traditional mailing that was sent to manufacturer's environmental staff as identified through the Interstate Mercury Education and Reduction Clearinghouse. The second notification was sent by electronic mail (email) to interested parties who are members of the Association of International Automobile Manufacturers and/or the Auto Alliance.

The report form was included in the email and was also available on the MPCA's web site. A new web page was posted specifically for the MAC program. Manufacturers sent completed reports to the MPCA by email to a project-specific address. Reports for over 360 makes and models from 17 manufacturers were submitted. A small number of manufacturers have no direct sales in Minnesota and do not report. MPCA staff compiled the reported data in a spreadsheet which was posted on the MPCA's MAC program web site and the Minnesota Attorney General's web site in December, 2008. Updates for newly-released vehicle models or changes to existing vehicle data will be made periodically, most likely on a quarterly basis.

In addition to data collection activities, the MPCA was directed to generate a report on the use, emission source, alternatives and cost effectiveness of control options for high-GWP gases in Minnesota that is consistent with the following requirements (Minn. Stat. §216H):

By February 1, 2009, the commissioner of the Pollution Control Agency shall submit a report to the chairs and ranking minority members of the senate and house of representatives committees with primary jurisdiction over environmental policy that identifies the uses and emissions sources of hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride in this state and suggests options for reducing or eliminating those uses and emissions and the costs of implementing those options. The options for reducing emissions must include phasing out specific consumer products containing high global warming potential gases where that is cost-effective.

Using information gathered pursuant to Minn. Stat. §216H.11, in consultation with various purchasers, contractors, wholesalers and manufacturers, MPCA staff, on behalf of the Commissioner of the MPCA, has prepared a review of the HFC, PFC and SF₆ uses in Minnesota, along with control options and phase-out alternatives, along with a discussion of cost for each sector.

1.2 Primer on High Global Warming Potential Gases

HFCs, PFCs and SF₆ are often referred to as “engineered gases.”² The primary reason that engineered gases are a concern is twofold. First and foremost, the source of these gases is almost exclusively human activity. While some very minor naturally occurring sources exist for some of these gases, they are not considered to be significant contributions to climate change.³ Secondly, the engineered gases identified in this report have very high global warming potentials that enhance the process of global warming.

The global warming potential (GWP) is a measure of how much a given amount (typically identified in units of mass) of an identified greenhouse gas is estimated to contribute to global warming. The GWP scale is relative in that it compares a gas species (e.g., HFC-134a) to the same mass of carbon dioxide. For the purpose of the GWP scale, carbon dioxide is considered to be a value of 1. The GWP is based upon the following factors:

- the amount and type of light energy absorbed by a given gas type (particularly infrared light); and,
- the amount of time the gas remains in the atmosphere (i.e., atmospheric lifetime)

The amount of time a gas remains in the atmosphere is an important factor as it reflects the ability of pollutant to remain an active greenhouse gas. To that end, a GWP is calculated over a specific time interval, typically 100 years. The GWP calculation process is discussed in greater detail in section 1.3 of this report.

Engineered gases are gases that have been produced through some manner of human-derived processes, designed to create a product for a specific set of uses. The history of engineered gases is relatively short, with most gas species developed within the past century. The largest sectors that rely upon engineered gases include refrigeration/cooling, electrical transmission, semiconductor production and various foams for firefighting and insulation. Most of the engineered gases in use today have been developed within the refrigeration sector.

Most refrigeration systems from the late 1800s until about 1929 used a variety of gases as refrigerants such as ammonia (NH₃), methyl chloride (CH₃Cl), and sulfur dioxide (SO₂). During this phase of refrigeration history, nearly any volatile substance was considered to be suitable as a refrigerant.⁴ While the “anything goes” phase of refrigerant gases provided a vast array of choices, it was noted that some of the substitutes presented workplace or home hazards. Typically, the hazards were related to toxicity, flammability or a combination of the two qualities. To address this concern, a collaborative industrial effort began between Frigidaire, General Motors and DuPont to develop a less dangerous refrigeration gas.

In 1928, Thomas Midgley, Jr., working with Albert Leon Henne and Robert Reed McNary, reviewed the periodic table of the elements in order to create a refrigerant that would be non-toxic and non-flammable, and still maintain the refrigeration qualities required for industrial, commercial and home use.⁵ The elements had to be stable, nontoxic, nonflammable, maintain a desired boiling point and have a high molecular mass (an important feature in controlling leaks). The result was the identification of a group of eight elements known as “Midgley’s elements” that include: carbon, nitrogen, oxygen, sulfur, hydrogen, fluorine, chlorine, and bromine.⁶

From the group of Midgley elements, the first chlorofluorocarbon (CFC) was created to replace the existing array of refrigerants. The new product was known as Freon.¹ The term “Freon” has become a generic term that represents several different CFCs used throughout the world in a wide variety of commercial and industrial uses. Unlike the previously used refrigerants, CFCs are colorless, odorless, nonflammable, noncorrosive gases or liquids. The lack of toxicity eliminated any danger to human health posed by refrigeration leaks. In 1930, Thomas Midgley held a demonstration of the physical properties of Freon for the American Chemical Society by inhaling a lung-full of the new wonder gas and breathing it out onto a candle flame, which was extinguished, thus showing the gas's non-toxicity and non-flammable properties.⁷

Shortly after their development, the use of Freon in refrigerators became standard for nearly all residential refrigeration units. The use of CFCs expanded to a variety of other applications including aerosols, air conditioning systems and foams. After several decades of commercial use, Lovelock (1973) reported finding trace amounts of refrigerant gases in the atmosphere from the northern hemisphere to the Antarctic.⁸ In 1974, Sherwood Rowland and Mario Molina predicted that CFC refrigerant gases would reach the high stratosphere, where they would be destroyed by ultraviolet radiation, releasing chlorine that would decompose ozone to oxygen, thereby allowing greater amounts of ultraviolet radiation to reach the surface of the Earth.⁹

ⁱ Frigidaire was issued the first patent, US#1,886,339, for the formula for CFCs on December 31, 1928.

Rowland and Molina were provided with dramatic evidence of their prediction when a hole in the stratospheric ozone was discovered over Antarctica in 1985.¹⁰

Engineered gases expanded in character, composition and design to meet specific performance characteristics for industry, heat transfer and a variety of other uses. Some of the recent engineered gases were developed to replace existing chemicals that were found to create problems with the Earth's ozone layer. Many of these gases are used to replace chemicals that have been restricted or banned under the Montreal Treaty (See sections 2.4.1 and 2.4.2).

1.2.1 Decoding HFCs and PFCs

Engineered gases are classified by their composition and the number of atoms within the molecule of each chemical. In the US, the classification standard is specified in the American National Standards Institute/ American Society of Heating, Refrigerating and Air-Conditioning Engineers (ANSI/ASHRAE) Standard 34-1992. Previously, the specified ANSI/ASHRAE prefixes were FC (fluorocarbon) or R (refrigerant), but today most are prefixed by a more specific classification. The prefix classification describes the types of elements found with the chemical structure:

Table #1 - Naming Scheme for Fluorinated Engineered Gases

Prefix	Name	Elemental composition
CFC	Chlorofluorocarbon	Cl, F, C
HCFC	hydrochlorofluorocarbon	H, Cl, F, C
HBFC	hydrobromofluorocarbon	H, Br, F, C
HFC	Hydrofluorocarbon	H, F, C
HC	Hydrocarbon	H, C
PFC	Perfluorocarbon	F, C
Halon	N/A	Br, Cl (in some but not all), F, H (in some but not all), C

Source: EPA - Numbering Scheme for Ozone-Depleting Substances and their Substitutes. (2008).

So generically, it is possible to decode a chemical by knowing the prefix (listed above) and the order of the numbers after the prefix. The numbers tell us the arrangement of the elements within the chemical. Using an example of the fictional chemical CFC-01234a, the numbers after the prefix relate to the following is:

- 0 = Number of double bonds (omitted if zero)
- 1 = Carbon atoms -1 (omitted if zero)
- 2 = Hydrogen atoms +1
- 3 = Fluorine atoms
- 4 = Replaced by Bromine ("B" prefix added)
- a = Letter added to identify isomers, the "normal" isomer in any number has the smallest mass difference on each carbon, and a, b, or c are added as the masses diverge from normal.

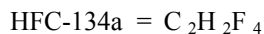
To decode HFCs and PFCs, we simply add 90 to the number following the prefix. While SF₆ is a fluorinated engineered gas, it is a single substance and is not included in the HFC/PFC categorical system. The number 90 acts as a key to decode the arrangement and number of atoms within the molecule of a particular chemical. In order to better understand the nature of the nomenclature, several examples are provided. The first example is the refrigerant HFC-134a.

First, we add 90 to the value of 134 which allows us to reveal the composition of the elements within the HFC-134a structure:

$$134 + 90 = 2 \quad 2 \quad 4$$

#C #H #F

This information tells us that there are a total of two carbons, two hydrogens and four fluorines, consistent with the arrangement presented above. There are no chlorines. The chemical formula is then written as follows:

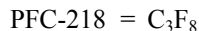


Another example is the chemical: PFC-218. Again, we add 90 to reveal the composition of the structure:

$$218 + 90 = 3 \quad 0 \quad 8$$

#C #H #F

In this situation, we can see that there are three carbon atoms, zero hydrogen atoms and eight fluorine atoms. It does not contain any other atoms.



In this situation, we can see that the prefix is consistent with the chemical composition: this is a PFC (perfluorocarbon), as it contains only atoms of F and C.

1.3 The Uses of Fluorinated Engineered Gases in Minnesota.

Fluorinated engineered gases are used extensively throughout Minnesota in a wide variety of applications. Generic uses of HFCs, PFCs and SF₆ are summarized below in Table #2.

Table #2 – Generic Use of HFCs, PFCs and SF₆ in Minnesota

HFC	PFC	SF ₆
<ul style="list-style-type: none"> • Refrigeration (Industrial, Commercial, Transport, Households, Stationary air conditioning, Heat pumps) • Mobile air conditioning • Foam • Solvents • Aerosols, Fire extinguishing, 	<ul style="list-style-type: none"> • Semiconductor manufacturing 	<ul style="list-style-type: none"> • Electricity distribution • Magnesium production • Semiconductor manufacturing

The contributions of greenhouse gases by economic sector in Minnesota are presented in Figure #1 and were adapted from the MCCAG Climate Change Action Plan. The emissions from industrial processes comprise the emissions of high-GWP gases. Emissions of HFCs from automobile air conditioning units and sulfur hexafluoride (SF₆) emissions from the utility sector increase the percentage of high-GWP emissions in Minnesota to approximately two percent of the statewide annual emissions of greenhouse gases.

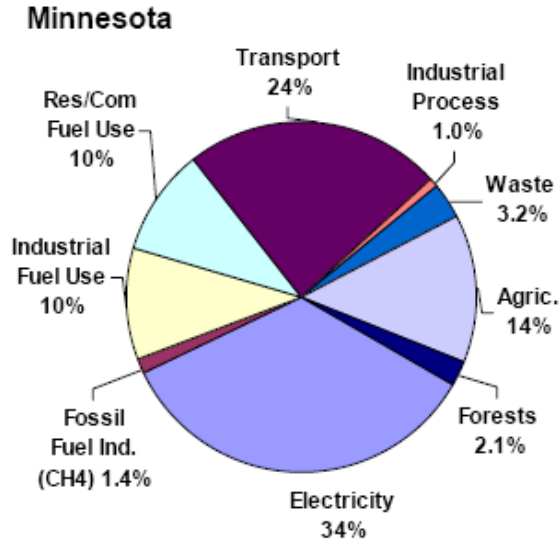
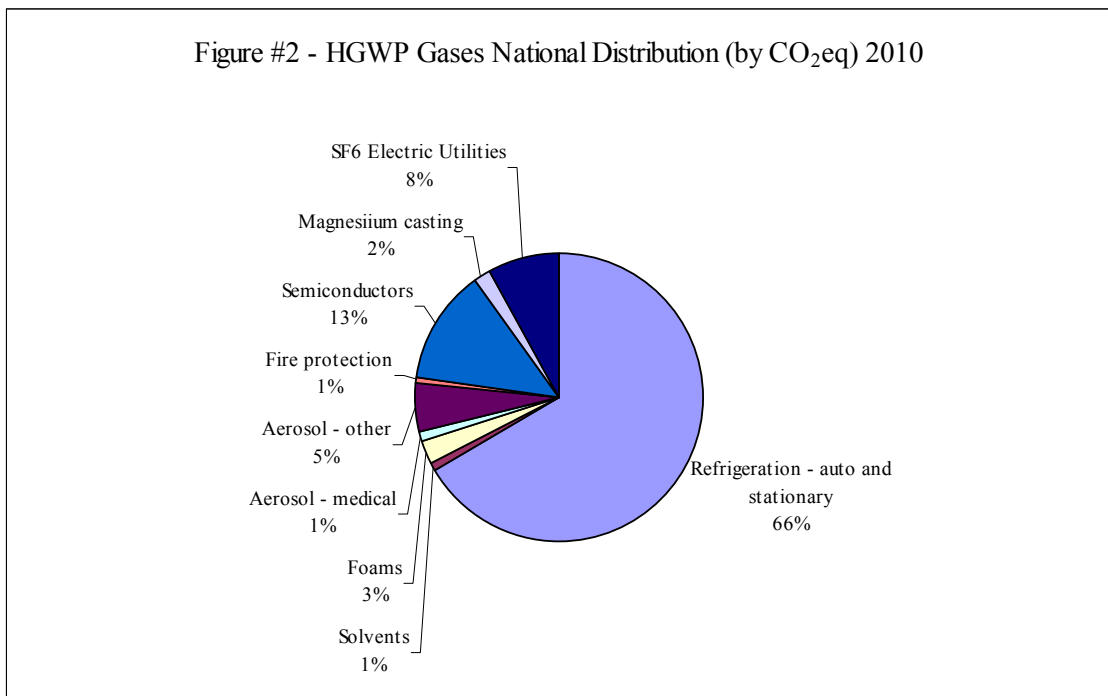


Figure #1 – Annual Contributions (percentage) of Greenhouse Gases by Economic Sector in Minnesota.



This percentage equates to approximately 3 million tons of carbon dioxide equivalent emitted annually. The distribution of contributions of high-GWP gases in Minnesota is likely to be similar to the national emission profile (See Figure #2). While high-GWP gas emissions may be small, they are typically emissions where control technologies or substitute gases exist. Reducing high-GWP gas emissions from the annual statewide emissions budget is a step in attaining the statewide emission reduction goals under the Next Generation Energy Act.

The MPCA high-GWP reporting data for 2007, required by Minn. Stat. §216H.11 is presented in Table #3. As previously discussed, a total of 3,260 letters were sent to MPCA permit holders and other affected parties on September 8, 2008. A total of 279 letters were returned as undeliverable. Of this amount, 47 were resent with updated addresses; however, the remaining 232 letters ultimately could not be delivered as no mailing address could be found. Our overall response rate for this effort was less than 2%, restricting the inferential value of the data for this Report. The following table is a breakdown of the reporting demographics:

Table #3 – High-GWP Reporting Response by Sector

Sector	Number of Reports Submitted	Approximate size of the sector
HVAC/Refrigeration	32	>5,000
Utilities	5	<200
Semiconductor	5	6
Fire Suppression	1	20,000
Consumer product	2	Not known at this time.
Foam Blowing Agent	1	52
Mag casting	1	20
Other	1	*
Manufacturers of high-GWP gases	5	30
Total Reports	53	

* This category represents to use of a high-GWP gas that does not fit into a specific sector category.

The 2007 reporting cycle for high-GWP gases was a useful pilot project in determining the administrative limits of the program.

The low response rates are likely a function of several factors: the data collection method, including the content of the MPCA letter; the management of the data collection process; and the 500 metric ton carbon dioxide equivalent reporting threshold. The language of the statute required purchasers of high-GWP gases that exceeded 500 metric tons (carbon dioxide equivalent) to report the purchase and to describe the use. The statute did not describe or define the scope of a purchaser for purposes of reporting under the statute. The MPCA designed the correspondence to address end-users of high-GWP gases. In an effort to minimize or eliminate double-counting, the MPCA requested that if a contractor or service provider managed high-GWP gases for a company, that the vendor or service providing should submit the report on behalf of their client. This approach was primarily designed to facilitate reporting in the refrigeration and heating/cooling sector.

The act of applying the statute in this fashion appeared to affect the response rate. Very few contractors provided a report. Those that submitted a report did so only for their own purchases and did not provide end use destination information. Several contractors contacted the MPCA and indicated that they were not willing to report as doing so would make their client list public, thereby revealing their client base to competitors. A number of companies contacted the MPCA and noted that their service provider or contractor operated out side of Minnesota. As many of the contractors did not make any purchase of high-GWP gases within the state of Minnesota, there was no legal obligation for them to make a report for themselves or their Minnesota clients. To improve the response rate, the next reporting cycle should require all purchasers of high-GWP gases to report purchases. The ability to categorize purchases allows for a greater ability to sort data by use and purchase without the potential for double-counting.

In addition, the MPCA did not create a specific category to account for those that make purchases of high-GWP gases that are below the reporting threshold or for facilities that do not make any purchase of high-GWP gases. This line of information provides context to the number of high-GWP users in the state and the amount that they may use over time. Future reporting procedures will include a means by which regulated parties are able to report their purchase status, thereby creating a more functional data set.

Finally, there was insufficient time between the effective date of the statute and the reporting deadline. The initial short reporting window affected our ability to create effective links with the association and trade organizations within this diverse collection of sectors. The ability to meet and with trade associations was considered paramount in light of the low reporting threshold (500 metric tonnes – carbon dioxide equivalent) and the relationship between purchases of high-GWP gases and emissions. In lieu of strong state data, national information on high-GWP gases was used to generate this Report.

1.3.1 Uses and Applications of HFCs

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

The HFCs with the largest measured atmospheric abundances are (in order), HFC-23 (CHF_3), HFC-134a ($\text{CF}_3\text{CH}_2\text{F}$), and HFC-152a (CH_3CHF_2). The only significant emissions of HFCs before 1990 were of the chemical HFC-23, generated as a byproduct of the production of HCFC-22. Between 1978 and 1995, atmospheric HFC-23 concentrations have increased from 3 to 10 parts per trillion (ppt), and continue to rise. Since 1990, when it was almost undetectable, global average concentrations of HFC-134a have increased significantly to almost 10 ppt. HFC-134a has an atmospheric lifetime of about 14 years and its abundance is expected to continue to rise in line with its increasing use as a refrigerant around the world. HFC-152a has increased steadily to about 0.3 ppt in 2000, however its relatively short life time (1.4 years) has kept its atmospheric concentration below 1 ppt.¹¹

1.3.2 The Uses and Applications of PFCs

It is important to distinguish between PFC gases and perfluorochemicals, also referred to as PFCs. Perfluorochemicals have been used to create products that resist heat, oil, stains, grease and water. This material is not the same substance that is the subject of this discussion. Gaseous PFCs have extremely stable molecular structures and are largely immune to the chemical processes in the lower atmosphere that break down most atmospheric pollutants. Not until the PFCs reach the mesosphere, about 60 kilometers (approximately 37 miles) above Earth, do very high-energy ultraviolet rays from the sun destroy them. This removal mechanism is extremely slow and as a result PFCs accumulate in the atmosphere and remain there for several thousand years. The estimated atmospheric lifetimes for CF_4 and C_2F_6 are 50,000 and 10,000 years, respectively. Measurements in 2000 estimate CF_4 global concentrations in the stratosphere at over 70 parts per trillion (ppt). Recent relative rates of increase in concentrations for two of the most important PFCs are 1.3% per year for CF_4 and 3.2% per year for C_2F_6 .

In general, PFCs are highly stable compounds that have unique chemical and physical characteristics, making them highly valuable for various specialized applications including:¹²

1. Semiconductor manufacturing processes (e.g., CF_4 , C_2F_6 , C_3F_8 , and $\text{c-C}_4\text{F}_{10}$);
2. Fire Suppression agents (e.g., $\text{n-C}_4\text{F}_{10}$, $\text{n-C}_5\text{F}_{12}$, and $\text{n-C}_6\text{F}_{14}$);
3. Precision cleaning solvents (e.g., $\text{n-C}_6\text{F}_{14}$);
4. Heat transfer fluids of coolants (e.g., perfluoro-1,3-dimethylcyclohexane);
5. Atmospheric tracers (e.g., perfluoromethylcyclopentane and perfluoromethylcyclohexane); and,
6. Aluminum smelting (e.g., CF_4 and C_2F_6).

1.3.3 The Uses and Applications of SF_6

The global warming potential of SF_6 is 23,900, making it the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. SF_6 is a colorless, odorless, nontoxic, nonflammable gas with excellent dielectric (insulating) properties. Like the other high-GWP gases, there are very few sinks for SF_6 , so all man-made sources contribute directly to its accumulation in the atmosphere. Measurements of SF_6 show that its global average concentration has increased by about 7% per year during the 1980s and 1990s, from less than 1 ppt in 1980 to almost 4 ppt in the late 1990's (IPCC, 2001). SF_6 is used in a variety of applications including:

- An insulating or arc-quenching gas in electrical equipment;
- Cover gas in magnesium foundries;
- Etchant in the semiconductor industry;
- Cushioning gas in running shoes and tennis balls;
- Electronic and high-voltage equipment;
- Degasser in aluminum foundries; and,
- Tracer and leak detection gas.

SF_6 is used for insulation and current interruption in electric power transmission and distribution equipment, in the magnesium industry to protect molten magnesium from oxidation and potentially violent burning, in semiconductor manufacturing to create circuitry patterns on silicon wafers, and as a tracer gas for leak detection. Historically, "Approaches to achieve the elimination of SF_6 include: combustion, chemical-thermal elimination, non-equilibrium plasma."¹³ One of the primary difficulties in degrading SF_6 is its high chemical stability. A combustion temperature of more than 1,100 degrees Celsius is required; however, the combustion is incomplete, with the highly reactive group of nitrogen oxides (NO_x) as a byproduct. A photochemical technique using propene appeared to be successful in decomposing SF_6 within laboratory test; however, there has not been any production-scale technology developed from this most current effort.¹⁴

1.4 Climate Change and Engineered Gases

Although emissions of engineered gases are very small in comparison to other greenhouse gases (around 2 to 4% of the overall global emissions), they are of particular concern because of their long life in the atmosphere.¹⁵ HFCs, PFCs and SF_6 have atmospheric lifetimes of hundreds to thousands of years and are actually far more potent greenhouse gases than CO_2 per unit of molecular weight.¹⁶

The HFC and PFC families are large, containing a diverse group of chemicals with vastly different characteristics. As a result, each chemical likely has a different role in the global warming process. In order to address this concern, we would need to develop a system by which we could evaluate and rank each gas based on their specific properties of global warming. To complete the analysis, we would need to answer the following questions:

1. Which are the most important gases that contribute to global warming?
2. How much does each gas species contribute to the warming process?

In order to address the first question, we need to calculate the GWP of a specific gas. There are two characteristics of a molecule that must be considered in this calculation. First, we need to understand how strongly it absorbs light and second, how long the molecule remains in the atmosphere before it degrades. Within the context of the GWP scale, carbon dioxide is used as a reference and has a defined global warming potential of 1. The GWP characteristics of CO₂ are such that it absorbs light energy with a particular strength and remains intact as a CO₂ molecule within the atmosphere for about 120 years.

As noted above, various engineered gases remain in the atmosphere for hundreds to thousands of years. The time frame for the GWP calculation becomes highly relevant. A chemical's GWP depends on the timespan over which the potential is calculated. A gas that is quickly removed from the atmosphere may initially have a large warming effect, but for longer time periods, as it is removed, becomes less potent. The typical timespans used for GWP calculations include 20, 100 and 500 years. The MPCA uses a 100 year timespan consistent with many other regulating entities and organizations.

In order to demonstrate the impact that a timespan has on calculating a GWP, the following example is provided for a 100 year time period. A molecule (HFC-example) that absorbs 1,000 times more strongly than carbon dioxide, is stable for only one year in the atmosphere, has a relative global warming potential on this time horizon given by the ratio

$$10 = [(1000 \text{ absorption units})(1 \text{ year}) + (0 \text{ absorption})(99 \text{ years})]/[(1 \text{ absorption unit})(100 \text{ years})]$$

Additional examples include methane, which has a GWP of 23 over 100 years but 62 over 20 years; conversely sulfur hexafluoride has a GWP of 22,000 over 100 years but 15,100 over 20 years. The GWP value depends on how the gas concentration decays over time in the atmosphere. This is often not precisely known and as such, the values should not be considered exact. For this reason when quoting a GWP it is important to give a timespan reference to the calculation.

The answer to the second question presented above is a bit more complicated. We need to calculate from the concentration and the absorption for each gas species how much warming will occur. Usually, warming is expressed as the equivalent increase in radiation from the sun. The heating due to the greenhouse gases is called "radiative forcing." The important point to note is that because the concentration of greenhouse gases has increased it is predicted that radiative forcing has and will increase. While this evaluation is beyond the scope of this report, it is a critical feature to a long-term program designed to address climate change.

1.5 Existing Legal Authority and Legislative Requirements

This section of the report addresses the legal issues related to climate change gases and the legislatively mandated content of this report. The MPCA investigated the regulatory status of engineered gases in Minnesota, along with the current authority of the agency to regulate greenhouse gases. This analysis was deemed to be relevant with respect to regulatory options assessed within the context of managing engineered gases in Minnesota.

1.5.1 A Review of Existing Legal Authority

MPCA staff conducted a review of existing state and federal statutes, rules, local governmental ordinances and case law to determine if engineered gases are currently regulated within Minnesota. In addition, MPCA staff reviewed existing statutes and rules to determine if the MPCA currently holds regulatory authority to address the use of engineered gases in Minnesota. The following is a summary of these evaluations.

1.5.2 Regulation of Fluorinated Engineered Gases in Minnesota

The state of Minnesota currently regulates CFCs via Minn. Stat. ch. 116 and Minn. Stat. §325E.38, enacted to implement features of the EPA regulations for ozone depleting gases.ⁱⁱ State law does not currently regulate the emissions of HFCs, PFCs or SF₆, however, amendments to the Clean Air Act (CAA) prohibit the venting of HFCs and PFCs to the outdoor air.ⁱⁱⁱ

A review of CFC authority is presented here since CFCs and HFCs are used in many of the same applications. Future control of HFCs may take advantage of current CFC regulatory structure.

The architecture of the state CFC program is functionally similar to the EPA program to address ozone depletion. The key features of the Minnesota approach include: prohibitions on venting CFCs to the atmosphere; prohibitions on various uses and practices (coolant in motor vehicles, solvents, propellants in party streamers and noise horns); creation of a requirement to recycle CFCs from automobiles, refrigeration and cooling equipment; and, requirements to certify CFC handlers and train and certify persons working with CFCs. The statute exempts medical uses of CFCs.

ⁱⁱ Under Title VI of the Clean Air Act (CAA), the EPA is responsible for programs that protect the stratospheric ozone layer, consistent with the Montreal Protocol. The specific actions are found under Title 40, Part 82 of the Code of Federal Regulations. See generally sections 608 through 612 of the CAA for additional information. The EPA's Stratospheric Protection Division manages these programs.

ⁱⁱⁱ Section 608 of the Clean Air Act prohibits releasing HFC-134a into the atmosphere. The prohibition on venting HFC-134a has been in effect since November 1995. In addition, the Final Rule on Venting and Sales of Refrigerant Substitutes (March 12, 2004; 69 FR 11946) sustains the CAA prohibition against venting HFC and PFC refrigerants. Knowingly venting HFC and PFC refrigerants during the maintenance, service, repair, and disposal of air-conditioning and refrigeration equipment (i.e., appliances) remains illegal under Section 608. The rule also restricts the sale of HFC refrigerants that consist of an ozone depleting substance to EPA-certified technicians. There is also the Direct Final and Concurrent Proposed Rule Amending the Definition of Refrigerant (April 13, 2005; 70 FR 19371). This rule amends the definition of refrigerant to make certain that it only includes substitutes that consist of a class I or class II ozone depleting substance. This rule-making also amended the venting prohibition to make certain that it remains illegal to knowingly vent nonexempt substitutes that do not consist of a class I or class II ozone depleting substance, such as HFC-134a and HFC-410A.

The statute specifically directed the MPCA to develop rules to regulate CFCs under Minn. Stat. §116.731, Subd. 6. The MPCA promulgated a set of rules to regulate CFCs under Minn. R. 7027. The rules apply to appliances containing refrigerants listed by the EPA, motor vehicle air conditioners and related systems on agricultural or recreational/off-road vehicles. The rules specifically adopt the EPA's regulations for the servicing of appliances and motor vehicle refrigeration systems, along with a standard of competence for managing refrigerant recycling and a state certification program for technicians. Elements of the program are administered through the MPCA's demolition regulation program with respect to the capture/recycling of refrigerant from air conditioning and refrigeration systems. The certification requirement under the statute requires that persons subject to certification may obtain certification from the MPCA or an equivalent federal certification system (Minn. Stat. §116.735). The MPCA no longer administers any form of CFC technician certification and relies entirely on the EPA-sponsored certification programs.

The EPA administers certification of technicians that reclaim, recycle or handle CFCs under Section 608 and 609 of the CAA. Section 608 of the Clean Air Act provides certification for technicians that service, repair, or dispose of refrigeration and air-conditioning equipment (i.e., appliances). The certification process is designed to minimize refrigerant emissions by maximizing the recovery and recycling of such substances. Technicians within the motor vehicle sector are certified under Section 609 of the CAA.^{iv} According to the EPA, this certification allows a technician to perform service on motor vehicle air-conditioning systems and to purchase R-12 and ozone-depleting substitutes that have been found acceptable for use in motor vehicle air conditioners.

The MPCA relies upon the EPA certification process to address the federal regulations and state statute. The EPA certification process is a one-time only training and certification event that is administered through third-parties. There is no central database of certificate holders, with third-party tracking nearly nonexistent. There is no mandate for continuing education. Enforcement of the regulations has been sporadic.

^{iv} According to information provided by the EPA, "The original regulation promulgated under section 609 was published in July 1992. That regulation established standards for equipment that recovers and recycles CFC-12 refrigerant from motor vehicle air conditioners, rules for training and testing technicians to handle this equipment, and record-keeping requirements for service facilities and for refrigerant retailers. A supplemental final rule published in May 1995 established a standard for equipment that recovers but does not recycle CFC-12, and training and testing technicians to handle this equipment." Retrieved from <http://www.epa.gov/Ozone/title6/609/justfax.html> [December 5, 2008]

2.0 Other State, National and International high-GWP approaches

With increasing attention being paid to the causes of global warming and to the potential for mitigating GHG emissions, regulatory policies and voluntary programs concerning high-GWP gases have been developed both in the U.S. and in other countries, particularly Europe. This section of the report will describe some of these programs to better illustrate the activities within Minnesota.

2.1 Federal actions

Because at this time there is no mandatory federal program for regulation of GHGs, this section focuses on existing EPA programs that may impact the use of high-GWP gases and on voluntary EPA programs designed to reduce emissions of high-GWP gases

2.1.1 EPA Refrigerant Programs¹⁷

The current use of high-GWP gases in the U.S. is strongly linked to regulatory efforts to reduce ozone depletion. CFCs and other engineered gases that are known to cause ozone depletion also are high-GWP gases, and the phase-out and ban of these chemicals under the Montreal protocol has therefore helped to reduce the amount of high-GWP gases emitted to the atmosphere.^v

EPA has established several programs in order to reduce emissions of ozone depleting gases, focusing mainly on gases used as refrigerants. The regulatory programs include requiring servicers to maximize recovery and recycling of ozone-depleting gases; certifying refrigerant handlers, technicians, and recycling equipment; limiting sale of refrigerants to technicians certified for the appropriate type of refrigeration; and requiring repair of leaks from larger equipment.

Due to the concern about ozone depletion, several substitutes to CFCs have been developed, including HFCs. These gases also have a high-GWP, but the EPA regulatory programs described above do not apply to engineered gas refrigerants, such as HFCs, that do not have the potential for ozone depletion.

2.1.2 EPA High-GWP Gases Voluntary Programs

Because of increasing concern about high-GWP gases that are not being phased out under the Montreal Protocol, EPA has developed certain voluntary programs to encourage the reduction of these gases.

2.1.2.1 GreenChill Advanced Refrigeration Partnership¹⁸

The GreenChill Partnership was formed in November 2007, and focuses on the reduction of ozone depleting and high-GWP gases from refrigeration in the supermarket industry. The Partnership is working to achieve a transition away from the use of ozone depleting refrigerants, and to minimize emissions of all refrigerants through the use of advanced technologies, strategies and practices that reduce leaks and the need to recharge refrigerant systems.

Individual stores can apply for Gold or Silver level GreenChill certification. Gold certification requires use of non-ozone depleting refrigerants and meeting either 1) a minimum level of storewide refrigerant emissions (less than 15%) and annual use of HFC recharge (1.25 lbs. of refrigerant per 1000 BTU/hour total evaporator cooling load), or 2) use only refrigerants with a GWP less than 150. Silver certification requires use of non-ozone depleting refrigerants and

^v The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty designed to protect the ozone layer by phasing out the production of a number of substances believed to be responsible for ozone depletion. The treaty was opened for signature on September 16, 1987 and entered into force on January 1, 1989 followed by a first meeting in Helsinki, May 1989. The Protocol has been subject to a variety of revisions since its initial implementation.

meeting the same level of storewide refrigerant emissions (less than 15) but a slightly higher minimum annual use of HFC recharge (1.75 lbs. of refrigerant per 1,000 BTU/hour total evaporator cooling load).

As of November 2008, the Partnership had 40 members, including Cub Foods, Whole Foods, and Supervalu, along with several manufacturers of refrigerant and refrigeration systems.

2.1.2.2 SF₆ Emission Reduction Partnership for Electric Power Systems¹⁹

SF₆ is used in the high voltage electric transmission system. EPA is working with the electric power industry to develop practices that help reduce emissions of SF₆. EPA has identified three major areas where SF₆ emissions can likely be cost-effectively reduced. These include leak detection and repair, recycling of SF₆, and employee education and training.

Power companies participating in this partnership estimate their annual SF₆ emissions, compile an annual inventory of their emissions with an emission inventory protocol, establish strategies for replacing older equipment (which is leakier and contains more SF₆ than modern equipment), implement recycling of SF₆, make sure only knowledgeable personnel handle the SF₆, and submit annual progress reports to EPA. EPA houses the emission data and shares the technical information on strategies that have been used to successfully reduce emissions.

Minnesota-based Great River Energy is a partner in this program.

2.1.2.3 SF₆ Emission Reduction Partnership for the Magnesium Industry²⁰

SF₆ is used by magnesium producers, casters, and recyclers as a “cover gas” for molten magnesium. The cover gas prevents oxidation of the magnesium, which can lead to large fires. Unfortunately, most of the cover gas is directly emitted to the atmosphere. EPA and the International Magnesium Association have committed to eliminating SF₆ emissions by the end of 2010.

Under the program, partners are to estimate their historical SF₆ use and usage rate, track and report their ongoing usage rate, optimize processes to reduce SF₆ use, evaluate and install systems that use a cover gas with lower GWP, and share information about SF₆ emission reductions. EPA assists in reviewing emission reduction strategies and technologies and sharing information regarding emission reduction projects and technologies used both nationally and internationally.

Minnesota-based partners include Twin City Die Castings and Product Technologies.

2.1.2.4 Voluntary Aluminum Industrial Partnership (VAIP)²¹

EPA has been working with the primary aluminum industry since 1995 to develop methods to reduce PFC emissions from aluminum production. Aluminum production involves running an electric current between a carbon anode and a cathode through an electrolytic process bath, into which alumina is fed; two PFCs (CF₄ and C₂F₆) are produced through an “anode” effect when the level of alumina in the bath falls below optimal levels. The level of PFC emissions is therefore highly dependent on production processes.

VAIP partners attempt to minimize the amount of anode effects, and thus PFC emissions, by optimizing the production process. This includes employee training, computer monitoring of the process, and changes in how the alumina is feed into the electrolytic bath. EPA estimates that

PFC emissions per metric ton of aluminum production fell 57% between 1990 and 2002, and that additional reductions should be achieved by 2010. Members of the partnership also committed in 2003 to reduce emissions of CO₂ from the consumption of the carbon anode during the process.

Partners agree to undertake cost-effective actions that reduce PFC emissions, track and record PFC emission reductions, and share information about successful PFC emission reduction processes. EPA houses the technical information on the emission reduction strategies, supports development of emission data, and assists in identifying and evaluating factors that influence PFC creation.

2.1.2.5 PFC Reduction/Climate Partnership for the Semiconductor Industry²²

Several PFCs are used in the basic procedures of semiconductor manufacture, etching circuitry onto silicon and for cleaning chemical vapor deposition (CVD) tool chambers. Emissions of PFCs to the atmosphere are extremely difficult to measure, as they can vary greatly due to process parameters; it is estimated that anywhere from 10 – 80% of the PFCs used may be emitted directly to the atmosphere.

The Partnership, begun in 1996, focuses on reducing emissions of PFCs through pollution prevention strategies, namely: process improvements/source reduction, alternative chemicals, capture and beneficial reuse, and pollutant destruction. It has, to this point, been easier to control emissions from the CVD processes than from circuitry etching. The goal of the World Semiconductor Council, and EPA partners, is to reduce emissions 10% below 1995 levels by 2010. In 2002, emissions showed a 37% improvement from 1999.

2.3 Activities in other States

Like Minnesota, many other States are beginning to look closely at ways to mitigate global climate change. Many States have had Climate Advisory Groups or similar bodies set up to investigate policies for reducing emissions of GHGs from within the State. These groups have generally included recommendations to develop methods for reducing the emissions of high-GWP gases, although very few (if any) States actually have on-the-books regulations for these gases.

2.3.1 California

Among U.S. States, California is often in the forefront on environmental issues, particularly on the issue of climate change. In 2006, California passed into law AB32, the Global Warming Solutions Act of 2006, which calls for a return to 1990 levels of GHG emissions by 2020. The California Air Resources Board (CARB) on December 11, 2008, adopted a Scoping Plan that lays out the strategies that will be used to reduce GHG emissions in California, including regulations, incentives, voluntary action, and market mechanisms including cap-and-trade.²³

As part of the AB32, and as described in the Scoping Plan, CARB is required to identify “Discrete Early Actions” to reduce GHG emissions that can be implemented by 2010. CARB has identified four such measures to reduce high-GWP emissions from mobile air conditioners, semiconductor manufacturing, consumer products, and air quality tracer studies.

In June 2008, CARB adopted a Discrete Early Action measure to reduce high-GWP gases in consumer products. Consumer products, in this case, include floor cleaner, aerosol air freshener, oven cleaner, paint and paint thinners, pressurized gas duster, and various other adhesives, cleaners, etc.

CARB is also proposing the establishment of a mitigation fee on high-GWP gases, as in many cases the price of the high-GWP gases are too low to prompt investigations into substitutes or alternatives. The fee would vary in proportion to the impact of the product on the environment and public health, and revenues are projected to be used to mitigate GHGs.

The following table, drawn from the AB32 Scoping Plan, lays out the measures recommended by CARB for reducing emissions of high-GWP gases and the projected emission reductions in CO₂-equivalent.

Table #4 - California High-GWP Gases Sector Recommendation (MMTCO₂-eq in 2020)²⁴

Measure	Reductions
Motor Vehicle Air Conditioning Systems: Reduction of Refrigerant Emissions from Non-Professional Servicing (Discrete Early Action)	0.26
SF ₆ Limits in Non-Utility and Non-Semiconductor Applications (Discrete Early Action)	0.3
Reduction of PFCs in Semiconductor Manufacturing (Discrete Early Action)	0.15
Limit High-GWP Use in Consumer Products (Discrete Early Action) (Adopted June 2008)	0.25
High-GWP Reductions from Mobile Sources Low GWP Refrigerants for New Motor Vehicle Air Conditioning Systems Air Conditioning Refrigerant Leak Test During Vehicle Smog Check Refrigerant Recovery from Decommissioned Refrigerated Shipping Containers Enforcement of Federal Ban on Refrigerant Release during Servicing or Dismantling of Motor Vehicle Air Conditioning Systems	3.3
High-GWP Reductions from Stationary Sources High-GWP Stationary Equipment Refrigerant Management Program: Refrigerant Tracking/Reporting/Repair Deposit Program Specifications for Commercial and Industrial Refrigeration Systems Foam Recovery and Destruction Program SF ₆ Leak Reduction and Recycling in Electrical Applications Alternative Suppressants in Fire Protection Systems Residential Refrigeration Early Retirement Program	10.9
Mitigation Fee on High-GWP Gases	5

At this point, CARB is still drafting the regulations to implement many of the Discrete Early Actions. Draft rule language is available for some rules. The rule to reduce the use of fluorinated gases from semiconductor manufacturing sets forth specific emission standards that must be met by new and existing sources after January 1, 2012. It also sets forth emission reporting and recordkeeping requirements. An initial emissions report must be submitted by March 2011, and annually thereafter.²⁵

Draft rule language is also available for SF₆ limits in non-utility and non-semiconductor Applications, with a note that CARB is still considering multiple options. The draft rule language available prohibits the purchase, sale, or use of SF₆ for all applications except a few specific exceptions for areas where no viable alternative exists. The expected dates of compliance are January 1, 2010 for most applications and January 1, 2013 for magnesium casting.²⁶

2.3.2 Connecticut²⁷

Similar to many other States, the Connecticut Governor's Steering Committee on Climate Change has recommended that the State investigate measures to reduce emissions of high-GWP

gases. The Steering Committee particularly called out the opportunity for emission reductions at supermarkets through a leak-reduction and maintenance program.

2.3.3 Illinois²⁸

The Illinois Climate Change Advisory Group was formed by the Governor to consider and make recommendations on appropriate strategies for reducing GHG emissions in the State. One of the policy options recommended is to “Encourage or require reductions in emissions of high-GWP gases (N₂O, HFCs, PFCs, SF₆).” The policy proposal encourages the adoption of State laws to limit the release of high-GWP gases.

2.3.4 Massachusetts

In August 2008, the Massachusetts enacted the Global Warming Solutions Act (Chapter 298 of the Act of 2008). The Act requires the Department of Environmental Protection to, among other things: develop a GHG registry and reporting system (or collaborate on a regional system); require annual reports of GHG emissions from any facility that reports emissions under Title V; require annual GHG emissions reports from any stationary source that emits greater than 5,000 MtCO₂-eq of GHGs annually; and allow for voluntary reporting of GHG emissions by other facilities.²⁹

2.3.5 New Jersey

The New Jersey Global Warming Response Act (S2114) defines HFCs, PFCs, and SF₆ as greenhouse gases, and requires the New Jersey Department of Environmental Protection to develop rules and regulations for GHG emissions monitoring and reporting.³⁰ The Department is still in the process of developing the required regulations. Preliminary presentations of draft regulations show a proposal for major stationary facilities to report all GHG gases, including all non-CO₂ gases with any level of emissions, while non-major stationary facilities would report only non-CO₂ gases where emissions were over 2,500 tons/year CO₂ equivalent (and would not report CO₂ or methane emissions).³¹

2.3.6 Wisconsin³²

Wisconsin has several laws, enacted in 1990, to prevent the release into the ambient air of gases used as refrigerants. Although these were put in place to limit emissions of ozone depleting chemicals, other high-GWP gases have been added to the list of refrigerants. The regulated gases include CFCs, HCFCs, HFCs, PFCs, and any blends of these gases.

The Wisconsin Department of Natural Resources (DNR) regulations mandate that refrigerants must be properly recovered when equipment containing them (air conditioners, refrigerators) is dismantled. Companies that recover refrigerants must be registered with the DNR, keep records of recovery activities, and supply documentation of proper recovery.

Wisconsin’s Department of Agriculture, Trade, and Consumer Protection regulates servicers of mobile air conditioners, requiring them to have licenses; the Department of Commerce performs the same function for stationary source refrigerant equipment and technicians. These regulations essentially mirror the federal requirements, but apply to a broader range of gases.

2.4 International Activities

Understanding international programs and activities for reducing or mitigating high-GWP gases requires a brief introduction to two major international environmental treaties: the Montreal Protocol and the Kyoto Protocol. The current status of high-GWP gas regulation around the world largely hinges on these two international agreements and their goals – preventing

depletion of the ozone layer and preventing climate change, respectively – which must both be understood when examining the potential for future regulation of high-GWP gases.

2.4.1 Montreal Protocol

The Montreal Protocol on Substances that Deplete the Ozone Layer was adopted in Montreal in 1987, and subsequently adjusted and amended in Meetings of the Parties in London (1990), Copenhagen (1992), Vienna (1995), Montreal (1997), and Beijing (1999). The Montreal Protocol is generally viewed as a highly successful international environmental treaty. It controls the consumption and production of chlorine- and bromine-containing chemicals that contribute to stratospheric ozone depletion, such as CFCs, methyl chloroform, carbon tetrachloride, and many others.

The Montreal Protocol has a large impact on current worldwide emissions of high-GWP gases. Ozone-depleting gases, such as CFCs, also have a high-GWP and therefore a strong impact on climate change. Without the Montreal Protocol, many more of these gases would be in general use, and many more would be in the global atmosphere. However, many of the alternatives to ozone-depleting gases that were developed to comply with the Montreal Protocol are also high-GWP gases. These gases are now coming under scrutiny due to their contribution to global climate change, though they remain important substitutes for ozone-depleting substances and often have a lower GWP than the ozone-depleting gases they replace.³³

2.4.2 Kyoto Protocol

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1997 at the Third Session of the Conference of the Parties to the UNFCCC. For those countries that have signed and ratified the Protocol, it contains legally binding commitments. Signatory Annex B countries (mainly developed and transitioning economies including members of the European Union (EU), Russia, Canada and others, including the non-ratifying U.S.) agreed to reduce their man made GHG emissions by at least 5% below 1990 levels by 2012. The Kyoto Protocol specifically covers six anthropogenic greenhouse gases: CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆. These gases have come to be known as the “Kyoto 6”, and are the main gases proposed for regulations in most programs to reduce GHG emissions.

Due to the Montreal Protocol and the Kyoto Protocol, many countries already have some programs in place to deal with emissions of high-GWP gases from the refrigeration sector; these primarily began as programs to contain ozone-depleting substances, but some have had other refrigerants added to the program. In particular “regulations that require recycling [of HFC refrigerants] have been enacted in many countries including Denmark, France, Germany, Iceland, Netherlands, Norway, Sweden, United Kingdom, and the United States, but are not always enforced” and recycling is not always profitable.³⁴

2.4.3 European Regulations

The European countries that are a party to the Kyoto Protocol have generally been the most active in adopting and implementing regulations to reduce GHG emissions.

2.4.3.1 General European Regulations³⁵

In 2000, the EU launched the European Climate Change Programme to identify and develop cost-effective actions to meet its Kyoto target. Some of the recommended actions focused on high-GWP gases, which the EU program refers to as fluorinated gases (or F-gases).

In 1995, European emissions of F-gases were 65 Mt CO₂-eq, about 2% of total European GHG emissions; without regulation, emissions were projected to be 98 Mt CO₂-eq as of 2010. In 2003, the European Commission proposed legislation to reduce emissions of these gases by 23 MtCO₂-eq by 2010. The European Parliament and Council adopted the legislation calling for reductions in May 2006.

There are two main parts of the EU's F-gas regulation. The first, Regulation (EC) No. 842/2006 (known as the F-Gas Regulation) covers mainly stationary source applications, while the second, Directive 2006/40/EC covers emissions mainly from motor vehicle air conditioning.

The F-Gas Regulation states, "Provision should be made for the prevention and minimisation of emissions of fluorinated greenhouse gases." The F-gas regulation primarily applies to stationary sources such as refrigeration, air conditioning, heat pumps, and fire protection systems.

The main provisions of the regulation include:

- Requirements for the prevention of leakage of F-gases, including scheduled checks for leaks or use of leakage detection systems; and quick repair of leaks;
- Required recordkeeping of the quantity and type of gases installed and added during maintenance, recovered during maintenance or final disposal, and identification of service technician;
- Requirements for operators to make arrangements for the proper recovery of F-gases from equipment;
- Required training and certification for companies and personnel that install, maintain, and service covered equipment;
- Reporting by producers, importers, and exporters of F-gases of the total amount of gases produced, imported, or exported, the main category of application of the gases, and any quantities that are recycled, reclaimed, or destroyed;
- Labeling of equipment that contains F-gases indicating the type of gas and quantity
- A prohibition on the use of SF₆ in magnesium casting after January 1, 2008, except in minimum quantities below 850 kg per year; and,
- Prohibitions on the placing on the market of certain specific products and equipment or applications that use F-gases; examples include a ban on use of PFCs in fire extinguishers, use of F-gases in windows (both in effect as of July 4, 2007), and a ban on HFCs in novelty aerosols that takes effect on July 4, 2009. Note that individual countries with more restrictive measures are allowed to keep those measures in place until the end of 2012.

The regulation also requires a report evaluating the application of the regulation, to determine the cost-effectiveness of the provisions, determine if other gases should be added to the list of F-gases, report on the status of technology for substitutions for F-gases, and generally evaluate the success of the various provisions in the Regulation. The report is to be complete by July 2011.

The general F-Gas Regulation sets forth only the basic provisions listed above. Several implementing regulations have therefore been promulgated to further define the requirements of the regulation.³⁶ The implementing regulations include:

- Regulation No. 1493/2007 sets forth the format to be used for reporting production, imports and exports of F-Gases;
- Regulation No. 1494/2007 establishes the form of the labels and labeling requirements for products and equipment that contain F-gases;
- Regulation No. 1497/2007 lists standard leakage checking requirements for stationary fire protection systems;
- Regulation No. 1516/2007 lists standard leakage checking requirements for refrigeration, air conditioning, and heat pumps;
- Regulation No. 303/2008 sets forth minimum requirements and conditions for certification of companies and personnel that install, maintain, and service refrigeration, air conditioning, and heat pump equipment;
- Regulation No. 304/2008 sets forth minimum requirements and conditions for certification of companies and personnel that install, maintain, and service fire protection systems and extinguishers;
- Regulation No. 305/2008 establishes minimum requirements and conditions for certification of companies and personnel that install, maintain, and service high-voltage switchgear;
- Regulation No. 306/2008 lays out minimum requirements and conditions for certification of personnel that recover F-gas based solvents from equipment;
- Regulation No. 307/2008 establishes minimum requirements for training programs for personnel that service motor vehicle air-conditioning systems; and,
- Regulation No. 308/2008 establishes the format for notification of the training and certification programs of member states.

These regulations set forth basic standards and minimum requirements; each EU member state must design their own regulations that are in keeping with these over-arching requirements. For example, each country must design its own training and certification requirements. Individual countries also set their own specific penalties for non-compliance.

It is estimated that the containment measures in EC No. 842/2006 have an average cost of €18 per ton of CO₂-eq. reduced, while the marketing and use restrictions have an average cost less than €1 per ton of CO₂-eq., although this varies depending on application.³⁷

The EU also set forth directive 2006/40/EC, which regulates the use of fluorinated gases in automobile air-conditioners. First, the directive bans air conditioning systems that use gases with a GWP greater than 150, unless they have a rate of leakage less than the maximum permissible limits set forth. This applies to all new vehicle types as of June 2008, and all new vehicles as of June 2009. The second phase of the rule is a total ban on any car air conditioning systems that use F-gases with a GWP greater than 150. The total ban will apply to all new vehicle types as of January 2011, and to all new vehicles as of January 2017.

2.4.4 Specific European Country Regulations

Some European countries have additional requirements that go beyond the EU Regulation. Those that are related to the provisions of the EU Regulation are allowed to stay in place through 2012.

2.4.4.1 Denmark

Denmark has additional prohibitions on placing new products on the market, beyond those specified in the general EU regulation; the country began phasing out F-gases in March 2001.³⁸ Since September 2002, Denmark has had a ban on the use of HFCs in gap-fill foam, district heating pipes, spray cans, and car tires. As of January 2007, GHGs cannot be used in refrigeration, air conditions systems, heat pumps, dehumidifiers, or similar applications that use 10 kg or more of refrigerant.³⁹

Danish regulations do have some exemptions. For example, high voltage (>1 KV) transmission systems, vaccine coolers, and mobile systems may use GHGs. In addition, any products for export, such as refrigerators, may contain HFCs and HFCs may be imported for use in products that are subsequently exported. Finally, it is possible to gain an exemption from these regulations if no alternative exists, the alternatives are technologically or economically infeasible, or greater GHG emissions would result from the use of the alternatives.⁴⁰

In addition, in December 2000, Denmark passed a tax on HFCs, PFCs, and SF₆. The tax is imposed when the F-gases, or products that contain such gases, are imported; Denmark does not produce F-gases domestically. The tax is proportional to GWP and based on Denmark's CO₂ tax; the total fee for each ton of any high-GWP gas is the gas's GWP multiplied by the level of the CO₂ tax, up to a certain maximum level. The CO₂ tax is 0.1 krone per kilogram of CO₂ emitted. For HFC-134a, that would be multiplied by the gas's GWP of 1,300, making the tax 130 krone per kilogram of HFC-134a. The tax for SF₆ would be considerably higher, however, there is a maximum level of 400 krone per kilogram for the tax.^{vi, 41}

Denmark has allocated at least 12 million krone for investigation into the development of alternatives to F-Gases and to subsidize implementation of known alternatives. It is estimated that the tax and the general ban have resulted in a reduction of GHGs equivalent to 49,000 Mt CO₂-eq in 2001, increasing to 150,000 Mt CO₂-eq in 2005, and likely increasing to the equivalent of 370,000 Mt CO₂-eq in 2010, while the cost of the tax and regulation combined is estimated at about 200 krone per Mt CO₂-eq.⁴²

2.4.4.2 Austria⁴³

Austria began the phase out of fluorinated gases in December 2002. The Austrian regulation on F-gases has as its goal the reduction and phase out of these gases, and is coupled with incentives for "early phase-out." The regulation includes procurement guidelines for cooling equipment in delivery services and the construction sector. In addition, many provinces in Austria have banned F-gases in the construction of houses that receive public financial support; this is expected to lead to a general adoption of alternatives to high-GWP gases in construction.

^{vi} When this law was passed, the CO₂ tax was \$11.40 per ton of CO₂ and the maximum tax level was equivalent to \$46,000 per ton of gas (Jensen, F. [Danish plan for regulating the industrial greenhouse gases](http://www.epa.gov/electricpower-sf6/documents/conf00_jensen.pdf). Presentation to U.S. EPA. http://www.epa.gov/electricpower-sf6/documents/conf00_jensen.pdf). At current exchange rates, the CO₂ tax is closer to \$17.35/ton and the maximum tax would be closer to \$69,000 per ton.

2.4.4.3 Norway⁴⁴

Like Denmark, Norway does not directly produce any F-Gases (although PFCs are produced as a byproduct of aluminum production.) As a GHG reduction measure, Norway has placed a tax on imports of HFCs and PFCs. The tax is also linked to a refund, which is paid to promote the safe disposal of these gases.

The tax is 190.50 Kroner or about €24 per Mt CO₂-eq, and is applied to imports of gases either on their own or in products. It would also apply to any national production, should such production arise. A refund equivalent to the tax is paid by the government to a collection company that shows proof of disposal of the gases through destruction. The collection company then passes the refund (minus costs of disposal) to the original company that disposed of the gas. Currently, only one company in Norway collects and disposes of these gases.

This measure is causing companies to pay more attention to leakage rates, move to alternative gases, and is promoting proper disposal and destruction of the gases. Although rates of imports of HFCs and PFCs continue to grow, they are now below what was projected for a business as usual scenario without the tax.

2.4.4.4 Netherlands

As part of its Kyoto agreements, the Netherlands has a goal of reducing their non- CO₂ greenhouse gases 35% from a 1990 baseline by 2012. The Dutch non- CO₂ greenhouse gas program is known as the ROB (Reductieplan niet- CO₂ Broeikasgassen) program, and is administered by SenterNovem, the Netherlands Agency for Innovation and Sustainable Development. The ROB program targets emissions of high-GWP gases in aluminum production, cooling, electric power and distribution, and semiconductor manufacture. Activities of the ROB programme are:

- Encouraging research into emission-factors and monitor emission levels from various sources;
- Funding research into new technologies;
- Encouraging the employment of existing reduction measures; and,
- promoting co-operation between government, industry organisations and companies.”⁴⁵

One particular policy relating to HFCs calls for a reduction of HFCs from the one Dutch industrial facility that manufactures high-GWP gases. The facility, owned by Dupont, emits HFC-23 during the production of HCFC-22 and in 1995 contributed half of all HFC emissions in the Netherlands. ⁴⁶

The facility has been regulated through a permit issued by the local province, and provided with technical assistance and a subsidy from SenterNovem. The permit sets a maximum level of HFC emissions, and the subsidy provided funds for the research and development of appropriate technology for the destruction of the HFCs. The installation of a thermal converter at this facility resulted in a reduction of annual HFC emissions of about 3.3 Mt CO₂-eq, at a cost of about €0.65 per ton CO₂ equivalent. ⁴⁷

2.4.4.5 Iceland⁴⁸

Like the other Scandinavian countries, Iceland appears to have largely banned the use of HFCs and SF₆ except in certain cases, such as refrigeration, pharmaceutical use, and use in electric

transmission systems. In the 2002 Climate Change Strategy, the government set forth a goal of reducing PFC emissions from aluminum production. The goal is for PFCs to be less than 0.14 Mt CO₂-eq per metric ton of aluminum produced; this goal has been achieved by both of the aluminum smelters in Iceland, and is an enforceable condition in the facility's permits. This has led to a reduction of about 300,000 Mt CO₂-eq of PFCs from 1990-2004, despite an increase in aluminum production.

2.4.4.6 Sweden

Sweden requires refrigeration and air conditioning equipment to keep the charge as low as possible and to use a gas with smallest effect on the climate (taking into account what is commercially available). To aid in recycling, different types of refrigerants cannot be mixed. Leakage checks and recovery rules apply to mobile sources as well as stationary sources.

The Swedish EPA's Climate Committee has suggested a tax on fluorinated greenhouse gases.⁴⁹

2.4.4.7 United Kingdom

In its climate regulations, the UK has largely focused its GHG emission reductions on carbon and carbon dioxide. This is now changing, and the UK is moving towards setting GHG emission goals based on all emissions of GHGs, not just CO₂. In its December 2008 report, the newly established Climate Change Committee recommended moving towards a system where emission budgets are set in overall greenhouse gas emissions, not just CO₂; they further suggest that reductions up to 15 Mt CO₂e in 2020 might be available from non- CO₂ GHGs.⁵⁰

Non-CO₂ gases from industrial processes make up about 2% of total UK GHG emissions (as of 2006), and about 80% of these emissions are from HFCs and SF₆. These emissions are estimated to have dropped by 67% (from 39 to 13 Mt CO₂-eq) between 1990 and 2006.⁵¹ A conservative estimate is that 3 Mt CO₂-eq of reductions of non- CO₂ gases are available at a cost of £40/ton CO₂-eq, with about half of those reductions from measures to decrease leakage of high-GWP gases from appliance and that promote substitutes for high-GWP gases.⁵²

In 2009, the UK will introduce "The Fluorinated Greenhouse Gases Regulations 2009" in order to implement the requirements of the EU Regulations.

2.5 Other Country Regulations

2.5.1 Japan⁵³

In order to meet its Kyoto goals, Japan has developed a "Kyoto Target Achievement Plan," which was approved in April 2005. The Plan has three main measures that are related to high-GWP gases. These are: 1) Follow-up on voluntary action plans established by industry; 2) develop and promote use of alternative materials; and 3) Recovery and decomposition of F-gases under the appropriate existing legislation.

The Japanese government has focused largely on the voluntary action plans for the reduction of high-GWP potential gases, in association with the industrial sectors that use these gases. Action plans on F-gases have been developed by 22 industrial associations covering eight industrial sectors. The Japanese government is encouraging the Japan Business Federation (Nippon Keidanren) to steadily implement the developed Voluntary Action Plans.

Table #5 - Voluntary Action Plans in Japan

Category	Gas	Association	Target in 2010
Production of F-Gases	HFC	Japan Fluorocarbon Manufacturers Association	70% (HFC-23), 14% (Other HFCs) reduction of emissions from 1995 base year
	PFC/ SF ₆	Japan Chemical Industry Association	30% (PFC), 75% (SF ₆) reduction of emissions from 1995 base year
Formed/Heat insulation materials	HFC	Japan urethane foam Industry Association	20% reduction from forecasted usage in 2010
		Japan polystyrene Industry Association	11.8% reduction from forecasted usage in 2010
		Japan expanded polystyrene Industry Association	30% reduction from forecasted usage in 2010
		Japan phenol form Association	68% reduction from forecasted usage in 2010
Aerosol	HFC	Aerosol Industry Association of Japan	20% reduction of emission ration during manufacturing 30% reduction from forecasted usage in 2010
		The Federation of Pharmaceutical Manufacturers' Associations of Japan	25% reduction from forecasted usage in 2010
Refrigerating and Air Conditioning Equipment	HFC	Japan Refrigerating and Air Conditioning Association	10% reduction of leakage rate from 2002
		Japan Vending Machine Manufacturing Association	Leakage emission per production unit: 0.75 kg Leakage emission per unit during maintenance: 0.8 kg
		Japan Automobile Manufacturers Association	20% reduction of amount used per production unit
		Japan Refrigerating and Air Conditioning Association	(Production of Home use AC units) 10% reduction of leakage rate from 2002
		Japan Electrical Manufacturers' Association	(Production of Home use refrigerators) Leakage emission per usage amount during production: less than 5%
Cleaning Use	PFC	Japan Electronics and Information Technology Industries Association	60% reduction of total emissions from 1995 baseline
Semiconductor Manufacturing	HFC PFC SF ₆	Japan Electronics and Information Technology Industries Association	(Semiconductor manufacturing) 10% reduction of total emissions from 1995 baseline (liquid crystal manufacturing) Less than total emissions of 2000
Use of electrical insulating gas	SF ₆	Japan Electrical Manufacturers' Association	Emission ratio during production at 2005: Less than 3%
		Federation of Electric Power Companies of Japan	Emission ratio during inspection at 2005: 3% Emission ration during disposal at 2005: 1%
Metal Product	SF ₆	Japan Magnesium Association	Basic Unit (amount used per production unit during production): Less than the basic unit in 2001

3.0 Analytical Approach to the Project

As described in section 1.0, several objectives of this Report are addressed through a systematic evaluation of various alternatives including control strategies and substitutes. The evaluations for control strategies, substitutes and related options is conducted by sector and based in part on cost factors using a literature review, meta-analysis and limited case study. This section describes the sources of data and information used in the analysis, and the various analytical approaches.

The foundation for the MPCA Report is the 2001 Environmental Protection Agency (EPA) *U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions* and the EPA 2006 *Global Mitigation of Non-CO₂ Greenhouse Gase* report. The MPCA has compared this work to other analysis and the specialty literature to better develop an understanding of options and alternatives with respect to performance and cost. The 2001 EPA report provided a projected hypothetical “business as usual” baseline for high-GWP gases with the assumption that no control technologies would be employed to abate emissions. The analysis then reviewed each sector in context to various control strategies in order to better develop a sense of the cost and effectiveness of each proposed alternative. The rationale for using the 2001 EPA report is based on the following factors.

The EPA work was written as part of a comprehensive GHG mitigation approach, similar in fashion to the Minnesota efforts outlined by the MGGAC and the Next Generation Energy Initiative. The cost data associated with various alternatives is presented for each sector using a discounted cash flow analysis. The EPA report presented the costs of emission reduction for each option on the basis of dollars per metric ton of carbon equivalent (\$/TCE), with costs presented in constant real year 2000 U.S. dollars for reductions in the year 2010. Upon completion of the emission reduction options cost analysis across all of the sources and sectors, the options were ranked in ascending order by cost. After ranking, a marginal abatement curve (MAC) showing the marginal emission reductions achievable at increasing costs of carbon (\$/TCE) was developed.

3.1 Sources of Data and Information

The data and information used in this report were obtained from the following sources:

- Review of existing high-GWP reports compiled by various public sector entities;
- Review of available specialty literature;
- Case study data; and,
- 2007 MPCA high-GWP chemical purchase and manufacturer reporting data.

As noted above, the foundation for the MPCA Report is the 2001 Environmental Protection Agency (EPA) *U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions* and the EPA 2006 *Global Mitigation of Non-CO₂ Greenhouse Gase* report. The EPA reports presented the following information:

- Baseline Emissions of High-GWP Gases. The source of the emissions in the United States was summarized, followed by a baseline forecast of U.S. emissions from that source through 2010.
- This baseline was estimated under a “business-as-usual” case scenario and assumes that no further voluntary actions are taken to reduce emissions.

- High-GWP Gas Emission Reduction Options and Associated Costs. Each chapter summarizes the known technologies and practices for reducing the emissions from the source and estimates a cost for reducing emissions in terms of dollars per metric ton of carbon equivalent (\$/TCE).

The MPCA uses this presentation format throughout the various sectors analyzed. Other bodies of information, including peer-reviewed and professional specialty literature, were used to augment and update various features of the EPA analysis. The 2007 high-GWP chemical purchase and manufacturer data was augmented with information from various published works and from information collected through a series of discussions with industry.

3.2 Literature Review and Industry Contacts

A number of engineered gas evaluations have been conducted by the public sector in other states, at the federal level and internationally. Several of these works were selected and reviewed to develop a benchmark assessment of potential alternatives, substitutes and practices. The title of the specific work, name of the publishing entity or authors and general content are described in Table #6. This list is not exhaustive as other public, private and non-profit sector publications were also reviewed. All works are referenced at the end of the Report.

Table #6 – Summary of the major Fluorinated-gas publications used in this Report.

Title	Year	Author/Publishing Entity	Summary
Fluorinated Greenhouse Gases in Products and Processes: Technical Climate Protection Measures.	2004	Federal Environmental Agency (Germany)	Information on the different uses of fluorinated greenhouse gases and describes technically and economically feasible emission abatement measures in Germany.
Estimate of U.S. Emissions of High-Global Warming Potential Gases and the Cost of Reductions.	2000	Environmental Protection Agency (USA)	Designed to provide information on the different uses of fluorinated greenhouse gases and describes technically and economically feasible emission abatement measures in the United States and abroad.
U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions.	2001	Environmental Protection Agency (USA)	This report presents the EPA's forecast for f-gas emissions through 2010 under a business-as-usual scenario using the Vintaging model. It provides a cost evaluation of technologies and practices that can be used to reduce emissions, and the projected costs of reducing emissions.
Abatement of Emissions of Other Greenhouse Gases: "Engineered Chemicals"	2001	ECOFYS – IEA Greenhouse Gas R&D Programme	Global economic assessment of the current and future impact on climate resulting from emissions of halogenated greenhouse gases.
Emission Reduction Opportunities for Non-CO ₂ Greenhouse Gases in California	2005	ICF Consulting – California Energy Commission	Designed to present an assessment and abatement options on methane, HFCs, PFCs and SF ₆ within California. Includes sources not typically assessed under other approaches.
Emissions and Emission Projections of HFC, PFC and SF ₆ in Germany – Present State and Development of a Monitoring System.	2005	Federal Environmental Agency (Germany)	An overview of fluorinated-gas emissions in Germany with projections forecast for 2010 and 2020.
The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol.	1999	UNEP – Report to the Technology and Economic Assessment Panel HFC, and PFC Task Force.	The document presents linkages between the ozone depleting gases, high-global warming substitutes and the Montreal and Kyoto Treaties.
Reduction of Perfluorocompound (PFC) Emissions: 2005 State-of-the-Technology Report.	2005	International SEMANTECH Manufacturing Initiative.	Reviews current PFC technology development and implementation and describes the semiconductor industry emission reduction options.
FINAL Minnesota Greenhouse Gas Inventory and Reference Case Projections 1990-2025.	2008	Prepared for MCCAG by the Center for Climate Strategies.	An inventory of greenhouse gases and using existing data sets – specific to Minnesota.
Global Mitigation of Non-CO ₂ Greenhouse Gases	2008	Environmental Protection Agency (USA)	Comprehensive review of noncarbon greenhouse gases with a focus on baseline emissions, mitigation and cost.

3.2.1 Selection and Evaluation of Alternatives

In order to evaluate a substitute or alternative, a suite of criteria are typically developed to evaluate the various options. With many situations, generic criteria (e.g., cost factors) may be sufficient. In light of the numerous sectors evaluated in this project, there is recognition that each sector operates under conditions that are unique to a process or specific to the industry. Specific sector-based evaluation criteria were developed using published literature and the various contacts used as part of the analysis. The MPCA relied heavily on work by EPA to identify and

evaluate alternatives. The evaluation methodology used in the 2001 and 2008 EPA reports was the primary architecture for the MPCA evaluation.

The EPA analysis builds from a global baseline of non-CO₂ emission projections from 1990 to 2020.⁵⁴ From the baseline data, considered to be the “business as usual” or “no control” option, mitigation options were applied for each economic sector. The baseline was then assessed to determine the change between the control and no-control options. A cost/benefit analysis for each mitigation option, along with a technical abatement potential and breakeven price was calculated for each control option. A discussion of the sector-specific findings is included in each sector discussion.

One of the tasks directed by the Legislature was the evaluation of options. The MPCA relied upon the EPA option abatement potential evaluation for each of the various control strategies available to reduce the emission of high-GWP gases. The calculated total abatement potential for each mitigation option in (by sector) is equal to an option’s technical applicability multiplied by its implied adoption rate multiplied by its reduction efficiency (See Table #7).

Table #7 – Calculation of an Option Abatement Potential (EPA, 2006).

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

The sector-specific abatement potential is provided in each sector discussion. Another important parameter is the breakeven price of an alternative or option. The EPA calculated an option breakeven price for mitigation options to determine at what carbon price a mitigation option becomes economically viable (i.e., where the net present value of the benefits of the option equals the net present value of the costs of implementing the option). Mathematically, the relationship is expressed as follows:

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

The specific parameters of the evaluation are presented in Table #8:

Table #8 – Description of Parameters for the Breakeven Price Analysis

Parameter	Description
P	The breakeven price of an option, expressed as dollars per ton of carbon dioxide equivalent (\$/tCO ₂ eq).
ER	The emissions reduction achieved by technology expressed as metric tones of carbon dioxide equivalent (MtCO ₂ eg).
R	The revenue generated from energy production (scaled based on regional energy prices) or sales of by-products of abatement (e.g., compost) or change in agricultural commodity prices (\$).
T	The option lifetime/service life (years).
DR	The selected discount rate (%).
CC	The one-time capital cost of the option (\$).
RC	The recurring (i.e., operation and maintenance) cost of the option (portions of which may be scaled based on regional labor costs) (\$/year).
TR	The tax rate (%).
TB	The tax break equal to the capital cost divided by the option lifetime, multiplied by the tax rate (\$).

This net present value benefits/ net present value costs relationship can be arranged to evaluate a breakeven price, assuming that the emissions reduction (ER), recurring costs (RC), and revenue generated (R) are not subject to change in a given year:

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

The EPA did not include transaction costs in the price analysis as there were no specific policies or mandates that would encourage or facilitate the adoption of control technologies or management practices to abate emissions. This assumption is suitable for our current regulatory climate in Minnesota. The EPA used a discount rate of 10%, a tax rate of 40%, and dollars based on their value in the year 2000.⁵⁵

The EPA used marginal abatement curves (MACs) to determine the series of breakeven price calculations for the suite of available options for each sector and region. The MAC curves are used to identify the amount of potential emission reduction at varying price levels. Each point along the curve indicates the abatement potential given the economically feasible mitigation technologies at a given carbon price (See Figure #3). The x-axis of the diagram indicates the amount of emissions abatement in units of MtCO₂eq, with the y-axis illustrating the breakeven price in \$/tCO₂eq required to achieve the desired level of abatement. The EPA noted that functionally, the low-cost abatement practices are implemented first; with the curve becoming vertical at the point of maximum total abatement potential. The maximum total abatement potential reflects the sum of abatement across all options in a given sector.

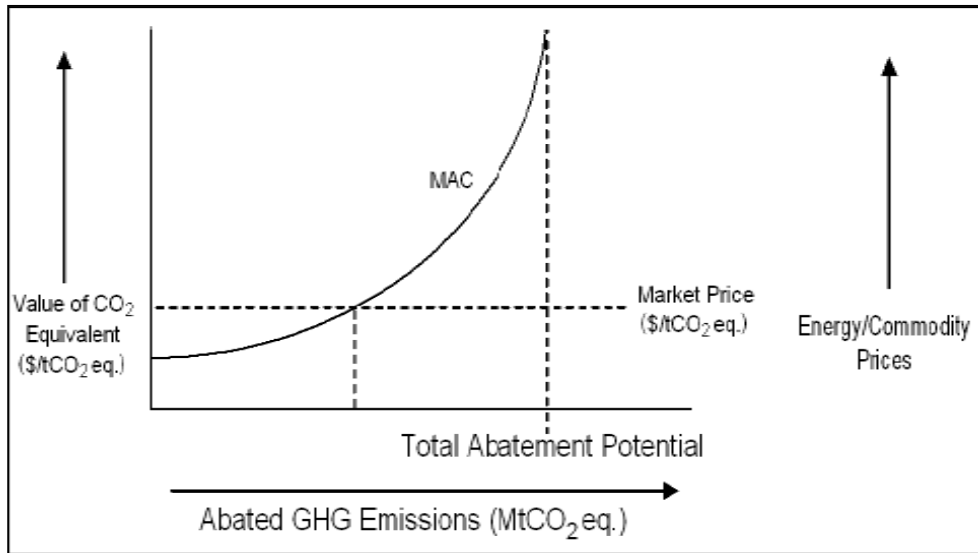


Figure #3 – Generic Marginal Abatement Curve for Greenhouse Gas Emissions.

Each of the sectors analyzed in this Report will include the results of the EPA evaluation in context to the literature reviewed and the information provided by industry. The MCCAG recommended that reductions costing less than \$15/tCO₂eq should be considered in regulating high-GWP gases. This value is used within the MPCA evaluation unless otherwise noted.

Some sectors include two marginal abatement curves: a “no-action” or “business as usual” curve and a technology adoption curve. The technology adoption curve was provided for some sectors where control technology has been applied. Through this approach, the marginal abatement curve is better able to illustrate the nature of a particular economic sector’s high-GWP emission status, resulting in a more credible analysis of control technology adoption and effectiveness through 2020.

4.0 Refrigeration and Cooling Sector

This section covers refrigeration and cooling in the industrial, commercial, residential and automobile sectors. The purpose of combining these sectors into one group is the common usage of refrigerant types and substitutes, along with the application of alternative practices. Each sector is described in greater detail within the section. This initial discussion is offered to present some general aspects of the refrigeration and cooling sector that can be applied broadly to all uses.

The refrigeration and cooling sector relies on refrigerants to collect and transfer heat in a refrigeration system. Refrigerants may be divided into four classes according to their composition:

Table #9 – Classification of Refrigerants by composition (After Tam, 2008)

Class	Description
Halocarbons	This is a group of refrigerants that are created from hydrocarbons by substituting chlorine or fluorine for the hydrogen atoms in ethane and methane. They are known as halogenated hydrocarbons and sometimes referred to as <i>Freons</i> . Common refrigerants in this group include R-11, R-12, R-13 and R-22. These groups of refrigerants are engineered gases.
Azeotropes	An azeotrope is a mixture of two substances that cannot be separated by distillation. It evaporates and condenses as a single substance with its properties completely different from its constituents. For example, R-500 is a mixture of R-12 and R-152. These groups of refrigerants are engineered gases.
Hydrocarbons	Gases that are produced from petroleum in an oil refinery. Examples include Ethane, propane, butane and isobutene. Typically, these gases are considered organic (containing both hydrogen and carbon atoms), naturally occurring gases – despite being the byproduct of industrial processing.
Inorganic Compounds	Carbon dioxide and ammonia are considered to be inorganic compounds as they do not contain a carbon and hydrogen atom. Both carbon dioxide and ammonia have been used as refrigerants for over a century.

To understand the various alternatives and substitutes available within the refrigeration and cooling sector, it is helpful to have an overview of the various refrigeration techniques. Functionally, there are two types of refrigeration systems currently in use: mechanical and thermal.⁵⁶ For the purpose of this Report, thermal refrigeration systems were not reviewed as there are very few thermal systems in Minnesota at this time.

A mechanical refrigeration system relies upon an engine to drive a closed vapor compression cycle and is used widely within the entire refrigeration and air conditioning sector (See Figure #4). It is often referred to as the vapor compression refrigeration system.

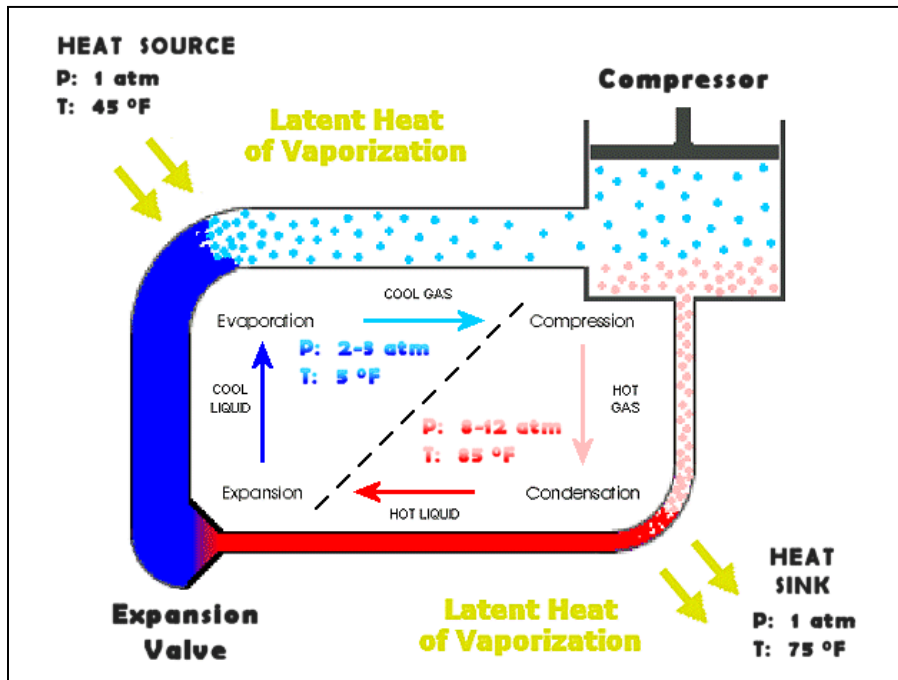


Figure #4 – Model of the Vapor Compression Refrigeration Cycle.⁵⁷

It is comprised of four operations: evaporation, compression, condensation and expansion.⁵⁸ The selected refrigerant travels through each of these processes, collecting, transporting and disposing of heat energy from the cooling area. The energy efficiency of this type of refrigeration system is assessed through what is known as the coefficient of performance (COP) and reflects the ratio of input (energy/work) and output (cooling effect).^{vii}

The mechanical refrigeration system is the most commonly used method for refrigeration and cooling. The various points of connection between the refrigeration components are potential sources of refrigerant leak. An ideal refrigerant or refrigerant substitute should be selected with consideration for the evaporating temperature required during operation, the coefficient of performance COP, safety requirements, and the size and location of the refrigeration plant.

4.1 General Areas of Abatement and Control

HFCs are used as the refrigerant in nearly every stationary and mobile source refrigeration and air conditioning system. While there are many specific actions that can be taken to abate or control HFC emissions, most approaches can be classified into two categories:⁵⁹

1. Activities that aim to minimize emissions during manufacture, operation and disposal of the appliances and systems; and,
2. Substitutes for HFCs using halogen-free substances or techniques.

^{vii} The coefficient of performance (COP) is a ratio of the work or useful energy output of a system in comparison to the amount of work or energy put in to the system. It is a commonly used approach to measure the energy efficiency of heating, cooling, and refrigeration appliances. In essence, the higher the COP, the more efficient the device.

The first category of actions can be implemented for all stationary or mobile refrigeration and air-conditioning systems. The primary activities that fall into this area include:

- Keep the emissions during installation/production or repair as low as possible;
- Improve the tightness of the system by technical means;
- Monitor the tightness of the system by regular inspections and maintenance; and,
- Minimize or eliminate the emissions during disposal.

Within the second category of activities, measures to consider include:

- The selection of fluorinated gases with the lowest possible GWP; and/or,
- Reduce the refrigerant charge.

The measures and activities described above are not specific to any one sector, but are capable of being implemented within any of the refrigeration/cooling sectors described within this section.

4.1.1 An Overview of Some Well-known Refrigerant Substitutes

While there are a wide variety of refrigerant substitutes in existence, the most commonly identified substitutes include carbon dioxide, hydrocarbons, ammonia, and to a lesser extent, dimethyl ether. The primary justification for the use of these substitutes is a function of cost and thermodynamic properties that make them excellent refrigerants. Each of the gases presents some constraint on use such as flammability, toxicity or equipment needs. The description provided below is a summary of each gas substitute.

4.1.1.1 Carbon Dioxide (CO₂)

Carbon dioxide is considered to be a natural refrigerant (R-744) and is also used as a propellant in spray cans, foam production and as an agent in fire suppression. One of the benefits of carbon dioxide is that it is typically a byproduct of a wide variety of industrial processes so it is not necessary to generate the gas for a specific purpose. As noted by the German government, "...CO₂ can be implemented without having an additional impact on the climate, since it would have been emitted into the atmosphere anyway."⁶⁰

Carbon dioxide has several characteristics that make it a suitable substitute for refrigeration and other uses. It is not toxic, flammable or corrosive and is odorless and chemically stable. It liquefies under pressure (a key requirement as a refrigerant) and is heavier than air.

The issues of concern include contact with liquid carbon dioxide and the potential for "dry ice" burns. In addition, the refrigeration lines required to use carbon dioxide as a refrigerant must be kept at very high pressure, elevating concern of substantial damage in the event of a blow out. As carbon dioxide displaces air, there is a potential suffocation danger. It was noted that carbon dioxide concentrations of 10 to 20% can be considered life threatening.⁶¹

4.1.1.2 Hydrocarbons

The hydrocarbon group includes propane (R 290), butane (R 600) and isobutene (R 600a). Mixtures of these gases are used as propellants in spray cans. Individually, they are used as refrigerants in a variety of domestic and small commercial refrigeration systems. One of the benefits of these gases is their natural occurrence, making them natural refrigerants. They tend to be odorless and not toxic; however, they are highly flammable. They reportedly have a drug-like effect at high concentrations.⁶²

4.1.1.3 Ammonia

Ammonia is a naturally occurring gas and has been used as a refrigerant (R 717) in commercial and industrial cooling for over a century. It is generally considered to have excellent thermodynamic properties and low cost, making it a very good substitute for many refrigeration applications. It is colorless and has a pungent odor. It is an ignitable gas though not as flammable as the hydrocarbon group illustrated above.

There are some health and environmental concerns associated with the use of ammonia. It is considered toxic if inhaled (lethal in concentrations typically greater than 10,000 ppm) under certain concentrations is also a known caustic (typically above concentrations greater than 700 ppm), burning eyes, skin and the respiratory system. Ammonia is highly water-soluble and very toxic to aquatic organisms. Contact with liquid ammonia will result in frost bite.

4.1.1.4 Dimethyl Ether (DME)

DME is typically used as a spray can propellant but is also used as a refrigerant. It is nearly odorless and as a liquid propellant, maintains some solvent properties. DME is slightly soluble in water, creating a potential environmental hazard if released to the environment. It is considered non-toxic, though inhalation of high concentrations are reported to have a drug-like effect.

4.2 Industrial and Commercial Refrigeration

The industrial refrigeration sector is composed of three applications:

- a. Process refrigeration: an integrated component of the production process (e.g., food processing);
- b. Industry refrigeration: freezing of products; and,
- c. Storage refrigeration: conservation of products.

The size of industrial refrigeration systems was classified according to the amount of refrigerant contained in the system. Small installations contain between 3 to 30 kilograms of refrigerant; medium sized systems contain between 30 to 300 kilograms of refrigerant, with large systems containing more than 300 kilograms of refrigerant.⁶³

4.2.1 Sector Overview

Minnesota is home to a wide variety of food processing endeavors that rely upon various forms of refrigeration and freezing to preserve and market their products. In addition, commercial refrigeration has a substantial presence in Minnesota including supermarkets, restaurants, coffee shops, and ice rinks. According to *Hospitality Minnesota*, there are approximately 9,000 restaurants in Minnesota. About half of the facilities are in the Twin Cities metro area. Of the overall total, approximately half of the restaurant facilities are identified as “quick service” restaurants (i.e., fast food), with the remaining half of the restaurant sector operating as table service facilities. In addition, there are approximately 1,400 resorts and campgrounds in our state and about 1,300 hotels, motels and Bed and Breakfasts. The *Minnesota Licensed Beverage Association* (MLBA) and the Minnesota Department of Public Safety – Alcohol Enforcement Division indicated that there are approximately 6,000 commercial/retail liquor operations currently licensed in the state of Minnesota. Each of the commercial operations maintains some form of refrigeration system that is likely serviced by a refrigerant that possibly contains HFCs or PFCs.

Another presence included in the commercial and industrial refrigeration and cooling sector are ice skating facilities. The Minnesota Ice Arena Manager's Association (MIAMA), a volunteer organization of ice arena managers and related vendors throughout Minnesota, other states and Canada. It has a membership of over 182 arenas. Ice arenas use a variety of refrigerants to maintain ice cover. According to MIAMA, over 90% of ice rinks in Minnesota use either R-22 or ammonia as a refrigerant, with R-22 the more commonly used system.

4.2.2 Alternatives

Alternatives within the industrial and commercial refrigeration and cooling sector range from changes in refrigerant types (known as “substitutes”) to major design and operation changes.

4.2.2.1 Control Technology & Research

Based on work conducted by the United States Environmental Protection Agency, a wide variety of alternative technologies for refrigeration and air-conditioning were reviewed and assessed using performance metrics.⁶⁴ The alternative refrigeration systems were compared in context to the standard mechanical vapor compression cycle systems described previously. The research project, identified and classified various refrigeration technologies based on patent information dating from 1918 to 1995, followed by a thermodynamic analysis of systems that appeared to have some promise of performance. Lastly, systems that achieved a favorable thermodynamic analysis underwent a technical assessment to evaluate the effectiveness of the alternatives. The technical assessment focused on two primary factors: environmental acceptability and system cost. The authors identified environmental acceptability through the following factors:⁶⁵

1. Ozone depletion potential (ODP) of the working material;
2. Global warming potential of the refrigerant technology;
3. Toxicity of the working material;
4. Flammability of the working material; and,
5. Noise generated by the system.

The system cost factors followed a similar arrangement:

1. State-of-the-art technology;
2. System size and weight;
3. System complexity;
4. Useful or service life;
5. Maintenance costs; and,
6. Efficiency.

The refrigeration systems were considered in context to the various operating sectors such as commercial, industrial and automotive. The conclusions of the study indicated that the mechanical vapor compression system of refrigeration was the most effective in all categories of operation. The authors also noted that the absorption refrigeration technology was an attractive commercial refrigeration technique; but may be too complex for use in residential systems.

With the mechanical vapor compression system operating as the preferred choice, an option within this framework relates to system configuration. One case study reviewed was the linkage between air conditioning and cooling systems within supermarkets. Supermarkets are considered to be the largest users of energy among US commercial buildings. A typical supermarket consumes around 2 million kWh per year. Many larger superstores can consume as much as 3-5

million kWh annually, with refrigeration typically accounting for around half of a supermarket's energy use.⁶⁶ The need for reduction in electrical consumption and a change in high-GWP refrigerants has created a number of alternative practices within the commercial and industrial refrigeration sector. The EPA reviewed a number of alternative practices including leak rate reduction, technician certification, recovery and recycling opportunities, replacement options and disposal methods.⁶⁷ The limitations on technician certification are presented in section 1.5.1.1 and will not be addressed here.

The first practice is the process of integrating refrigeration systems into the existing HVAC systems. This is possible through the use of water-source heat pumps. By incorporating the heat pumps in the heat rejection loop for the refrigeration, the rejected heat can be utilized for store space heating without increasing the condensing temperature of the refrigeration, and reportedly is capable of reducing operating costs by 12.6%.⁶⁸

Another approach is the use of a lower refrigerant charge to maintain the system. Under this approach, refrigeration and cooling systems can reduce charge levels by 50% or more through the use of distributed compressor systems and secondary-loop refrigeration. The systems employ several approaches that are designed to either minimize the amount of charge stored or reduce the use through careful regulation and control of the refrigerant.⁶⁹ The California Energy Commission (CEC) conducted an analysis of the cost effectiveness of these approaches within the cold storage warehouse sector, industrial process refrigeration sector, and the retail food refrigeration sector and can provide insight into the use of this technology to a broader application.⁷⁰

Within the sectors identified above, secondary loop systems were evaluated with ammonia and HFCs as refrigerants. The technology operates placing a refrigeration unit in a central location and then using a series of loops to circulate coolant or brine to display cases. Functionally, these systems operate at a reduced charge and generate fewer leaks. Both ammonia and HFCs were highly capable refrigerants in this case study. This approach is not currently employed in the United States to any great extent. It is a commonly used practice in Europe. Ammonia presents some constraints to operation in part due to toxicity, though leak detection is a fairly simple analysis. HFCs do not require the same level of attention. If ammonia is used, emergency diffusion systems and safety release valves are typically required.

Another application is the practice of replacing the single, direct refrigeration unit with multiple smaller refrigeration units located closer to the display case. According to work by the California Air Resource Board (CARB), this practice reduces the need for excessive refrigerant piping throughout the store and thereby reduces leak potential. In addition, the refrigerant charge need is also reduced. Based on work reviewed by CARB, there are also gains in energy efficiency and long-term cost performance. The results indicated that there is wide-spread use of this practice and that it is highly effective. The downside risk is that in light of placing refrigerant charge throughout a building, the potential risk of accidental refrigerant leak is substantial. In addition, the use of substitutes that are flammable or toxic may be excluded by local codes. Another concern is the amount of labor and leak detection.

Lastly, leak repair as an alternative practice that may lead to a reduction in HFC emissions was assessed by CARB for the industrial process refrigeration sector, cold storage warehouse sector, commercial air conditioning sector (unitary system), and chillers. Specifically, this was an

analysis of leak repairs and preventative maintenance. It included the installation of new purge systems, the replacement or removal of motors, installation of new metering systems, replacement of flare joints, gaskets and seals. The conclusion of the CARB evaluation indicated that this type of practice was only feasible for large systems or where a repair was warranted. The efficacy of this practice varies substantially due to the age of equipment and the quality of the repairs made. Ultimately, CARB noted that the reduction of refrigerant loss was uncertain due to the highly variable nature of the refrigerant system and the nature of the leakage.

4.2.2.2 Case study

A comparison of different refrigeration system arrangements was conducted by Walker (2000). The results of the comparisons are presented in the table below. Table #10 presents the findings of an energy consumption estimate for current multiplex refrigeration systems for a facility located in Washington D.C.. The results indicate that the distributed and secondary loop systems maintained similar results in comparison to the multiplex system. The annual energy savings were reported as between 11 and 12%.⁷¹

Table #10 – Refrigeration Energy Consumption Comparison (Walker, 2000).

System	Annual energy consumption (kWh)	Savings v. multiplex (kWh)	% savings v. multiplex
Multiplex – air cooled	976,800	n/a	n/a
Distributed air cooled	859,200	117,600	12.0
Distributed water cooled, evap.	865,100	100,700	11.3
Secondary loop, 4 brine loops, evap, condenser	867,400	109,400	11.2
Secondary loop, 4 brine loops, evap, condenser	967,100	9,700	1.0

Walker conducted an environmental assessment using the Total Environmental Warming Impact (TEWI) analysis for an operational service life of 15 years. A TEWI analysis is a combination of the direct emissions from the system and the indirect (energy-related) emissions, as they relate to global warming.⁷² According to the author, the lowest TEWI was achieved by the secondary loop system with water-cooled condensing and evaporative heat rejection. The results indicated a reduction of approximately 8.6 million kg (43.4%) of CO₂. A similar reduction was observed for the distributed refrigeration system.⁷³

Table #11 –TEWI Comparison of Supermarket Refrigeration Systems (Walker, 2000).

Refrigeration	Charge (kg)	Leak (%)	Annual Energy (kWh)	TEWI (Million kg CO ₂)		Total
				Direct	Indirect*	
Multiplex	1,300	15	976,800	10.00	9.82	19.82
Distributed air-cooled	680	10	859,200	7.34	8.63	15.97
Distributed, water-cooled, evap.	110	5	866,100	2.20	8.70	10.90
Secondary loop evap., condenser	230	10	867,400	2.45	8.72	11.16
Secondary loop water-cooled, evap.	90	5	967,100	0.49	9.72	10.21

One finding of note is that the use of alternative systems that reduce or eliminate high-GWP usage also save money. Walker reviewed the operating costs for a combined HVAC system with refrigeration for a commercial operation. It was noted that HVAC equipment is approximately 10-20% of the energy used in a supermarket, depending upon geographic location. A major feature of the supermarket store HVAC load is the presence of refrigeration units known as racks. The presence of the racks requires an even greater heating load in order to maintain ambient temperatures. An alternative practice in this situation is referred to as heat reclamation, in which a fraction of the refrigeration reject heat is reclaimed and used for space heating. It

operates by taking the hot gas from the refrigeration compressors and circulating them through heat exchanger coils that are located in the HVAC air-distribution system. Another innovation has been the use of a water-source heat pump that uses a glycol-loop for the transfer of refrigeration heat as a heat source. According to Walker, this is a better mechanism for heat transfer as it provides a much larger portion of the reject heat that can be recovered; and, the condensing temperature and head pressure of the refrigeration system do not have to be elevated.⁷⁴

Table #12 – Operating Cost Results for Combined Refrigeration and HVAC (Walker, 2000).

System	Operating Costs (USD)					Savings	
	Refrigeration	HVAC	Electric	Gas	Water		Total
Multiplex	Conventional		85,565	17,653	n/a	103,218	
Multiplex	Reclaim		90,519	8,967	n/a	99,486	3,732
Distributed air-cooled	Conventional		77,218	17,653	n/a	94,871	8,346
Distributed, water-cooled, evap.	WSHP		88,001	0	2,130	90,221	12,997
Secondary loop evap., condenser	Conventional		77,804	17,653	1,784	97,241	5,977
Secondary loop water-cooled, evap.	WSHP		95,258	0	2,130	97,388	5,830

A comparative analysis of these systems was developed by Walker using conventional rooftop units, refrigeration heat recovery, and water-source heat pumps. The results are indicated in Table #12. As both gas and electric energy were used to operate the systems compared, the comparison values are provided in units of annual operating cost (both refrigeration and HVAC). The values reportedly reflect local utility rates with operating costs that included both the fuel energy cost and water consumption cost for evaporative condensing systems. Based on the information provided, the lowest operating cost system was achieved with a distributed refrigeration arrangement with water-source heat pumps. The savings reported was \$12,997, or approximately 12.6% compared to a multiplex refrigeration and conventional rooftop HVAC arrangement.

4.2.2.3 Substitutes

A description of the most widely used refrigerant substitutes is found in 4.1.1. One of the most important tasks in the evaluation of refrigerant substitutes is the criteria selected for evaluation. In a published work by Calm (2002), five refrigerant selection criteria were identified:⁷⁵

- Future availability (or phase-out) based on controls for environmental protection;
- Efficiency;
- Toxicity;
- Flammability; and,
- Escalating future cost.

A sixth criteria added to this analysis is the cost of transition to substitute. A true “drop-in” substitute is not typical. Most systems require changes in lubricants, seals and potentially circulation lines. The four primary substitutes presented in 4.1.1 include carbon dioxide, ammonia, hydrocarbons and DME.

4.2.2.2.1 Future Availability

The future availability of all four refrigerant substitutes is presented in this analysis. The scope of the future availability analysis is based upon existing market information and government publications. Carbon dioxide, ammonia, propane and hydrocarbons are considered natural

refrigerants as they occur in nature, unlike engineered gases. Typically, the gas substitutes are generated as a byproduct of industrial processing.

Carbon dioxide is a byproduct of a vast number of industrial processes. Most CO₂ is obtained as a by-product from the production of ammonia, gasoline, and other chemicals. Other sources of carbon dioxide include fermentation, deep gas wells, and direct production from carbon-based fuels. In light of the wide variety of carbon dioxide production methods, an adequate and affordable supply appears to be available for all existing and future needs.

Ammonia, while naturally occurring, is produced commercially through the Haber-Bosch synthesis process.⁷⁶ Other industrial sources of ammonia include its formation as a by-product of the destructive distillation of coal, and its synthesis through the cyanamide process. In light of the production methods and existing uses, an adequate supply is available to meet the refrigeration needs.

Hydrocarbons, including propane, are naturally occurring gases at atmospheric pressure and can be liquefied if subjected to moderately increased pressure, making them ideal refrigerants. In general, it is not produced as a marketable product, but as by-product of natural gas processing and petroleum refining.⁷⁷

Dimethyl Ether or DME is used mostly as a propellant, though under some circumstances, can be used as a refrigerant. The factors affecting supply is likely the use of DME as a fuel in diesel and gasoline engines, along with gas turbines. It is currently being developed as a synthetic Biofuel that can be manufactured from lignocellulosic biomass.⁷⁸ This is a new market that is not fully developed with respect to processing, distribution and use. The availability and price of DME will likely be highly sensitive to changes in market usage. No statement on supply can be made at this time.

4.2.2.2.2 Efficiency

As previously discussed, the efficiency of a refrigerant reflects the amount of energy that must be added to the system in order for the gas to remove heat. In evaluating efficiency, it is important to understand that efficiency of a refrigerant reflects the systematic qualities of the unit, including compressors, condensers, lines, etc. Often, refrigeration units are designed to operate around a specific refrigerant. In addition, annual temperatures, heat load and specific use are all substantial factors in the operation of a refrigeration unit. Over the years, a number of comparative studies have been conducted to evaluate various refrigerants. The findings of these works are variable, often contradicting one another. This is likely a function of method and indicators selected to evaluate performance.

Table #13 – Physical characteristics, ozone depletion and global warming potential of selected gases.

Refrigerant	Normal Boiling Point (C°)	Density at 0° (C°) kg/m ³	Ozone Depletion Potential	GWP (100)
Carbon Dioxide	-25	0.013	0	1
Ammonia	-33	0.00035	0	0
Butane	0	0.0086	0	3
Isobutane	-12	0.0086	0	3
Propane	-42	0.008	0	3
Dimethyl Ether	-25	0.013	0	-

* Information derived from the Market Transformation Programme: BNCR37 – Characteristics of Refrigerants in Relation to Efficiency. Version 1.2. 2007.

The desired thermodynamic properties for a refrigerant include a boiling point that is somewhat below the target temperature; a high heat of vaporization; a moderate density in the liquid form

and conversely, a relatively high density in gaseous form; and, a high critical temperature. Boiling points and gas densities are affected by pressure. To that end, a selected refrigerant may be made more suitable for a particular application by choice of operating pressure; however, this may dictate a redesign of the entire refrigeration system. This is particularly the situation with ammonia and carbon dioxide.⁷⁹ The proposed substitutes identified in Table #13 are considered to have appropriate thermodynamic properties for a variety of refrigeration and air conditioning uses.

4.2.2.2.3 Toxicity and Flammability

Carbon dioxide, butane, isobutene, DME and propane have all been classified as having no identified toxicity at concentrations < 400 ppm. Ammonia has some toxicity as discussed in section 4.1.1.3. Carbon dioxide is not flammable at room temperature. Ammonia has a low flammability. The remaining substitute gases are defined as highly flammable.

Very pure forms of butane, especially isobutane, are used as refrigerants and have replaced the ozone layer depleting halomethanes in some household refrigerators and freezers. Typically, the amount of butane used in household appliances is small and not enough to cause a combustible mix given the amount of air in a room. In addition, the system operating pressure for butane is lower than for R-12, so R-12 systems such as in automotive air conditioning systems, when converted to butane will not function optimally, requiring a system upgrade, adding to the cost of substitution.

4.2.2.2.4 Escalating future cost.

The future costs for each of the identified substitutes is dependent on a number of factors including raw materials, processing, distribution costs and the presence of other demands for the same product within the marketplace. The future costs of hydrocarbons are directly connected to the fossil fuel market. Propane and butane prices are highly sensitive to changes in the market price for crude oil and natural gas. Recent fluctuations in global oil and natural gas supplies have impacted the price of propane and butane.⁸⁰ Other factors that may affect prices include competing uses for the same product, and storage/distribution issues. Carbon dioxide prices are not likely to fluctuate over time due to the abundance of the gas as a waste product. The production of ammonia is affected by fuel oil prices and market demand.

4.2.2.2.5 Transition Costs

As previously noted, the concept of a “drop-in” substitute is somewhat misleading in that the use of a substitute may require systematic changes in order to provide for the new product. While it is conceivable that a system would not require modification to operate with a substitute refrigerant, the need to implement various hardware changes (e.g., gaskets, seals, lines, etc) is expected and represents an additional cost to the substitute transition. For example, ammonia can be used with aluminum and steel, but not in the presence of water with copper and zinc delivery systems. Carbon dioxide requires operating pressures six times higher than traditional refrigerants. The higher pressure requires a redesign of delivery systems and complicates repairs. In this situation, the gas cannot be considered a true substitute as it is not replacing an existing refrigerant in an operating system.⁸¹ The use of the new gas represents an entirely new refrigeration system that translates to a new cost.

Each cooling and refrigeration scenario is unique to the space and load that is managed, the nature of the design and age of the equipment. While a specific transition cost cannot be

calculated for all systems, the factors that result in the determination of fixed and variable costs are easily determined.

4.2.3 Summary of Cost Issues

The EPA conducted a cost effectiveness analysis of various HFC emission reduction options in the industrial and commercial refrigeration and air conditioning sector. The evaluation was conducted in the context of a ten year service life with cost unit reductions expressed as cost per metric ton of carbon equivalent (TCE). The results of this analysis, based on the national EPA 2001 analysis, are provided in Table #14.

Table #14 – A summary of EPA Cost Effectiveness Analysis for various HFC Reduction Options.

Option	Market Penetration (%)	Cost (\$/TCE) and Discount Rate (%)		Sum of Reductions	
		4%	8 %	MMTCE	% of baseline emissions
Replacing direct expansion systems with distributed systems	10 to 20 % of retail food and cold storage market	\$0.02/TCE	\$7.21/TCE	1.5	4%
Leak reduction options	10% of retail food and industrial process markets; 5% of chillers, cold storage, commercial air conditioning, residential air conditioning, and motor vehicle air conditioning.	\$3.58/TCE	\$5.09/TCE	2.7	7%
Replacing HFC systems with HFC secondary loop system	10 to 20% of the retail food refrigeration market and 10 to 20% of the cold storage refrigeration market.	\$62.57/TCE	\$65.30/TCE	4.2	11%
Replacing HFC system with ammonia secondary loop system	10% of retail food, 10% of cold storage, 10% of industrial process refrigeration	\$98.61/TCE	\$108.67/TCE	4.8	12%

The EPA conducted a similar analysis in 2006 reviewing similar options and control strategies. The results of this analysis are found in Table #15. The 2008 EPA analysis predicted that the national baseline emissions for 2000 were 58 MtCO₂eq, with a predicted 148.6 MtCO₂eq in 2010 and 264.6 MtCO₂eq in 2020.⁸²

Table #15 – Summary of Abatement Option Cost Assumptions (2000\$) (EPA. 2008).

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

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

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

^c Includes parts and labor to perform repair job.

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

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

Of the options evaluated, leak detection and repair appear to be the most cost effective measures at controlling high-GWP gases. According to the 2008 EPA report, “Increasing leak repair of large equipment and refrigerant recovery/recycling from small equipment represents cost-effective options for reducing emissions from stationary equipment worldwide.”⁸³ Table #16 provides a global summary of the refrigeration/air conditioning breakeven costs and emissions reductions for the year 2020, based on the 2008 EPA report.

Table #16 – World Breakeven Costs and Emissions Reduction in 2020 for Refrigeration/Air Conditioning

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Direct Emissions Reduction (MtCO ₂ eq)	Indirect Emissions Reduction (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High					
Leak repair	-\$4.10	-\$4.10	4.91	0.00	0.8%	4.91	0.8%
Refrigerant recovery	-\$2.62	-\$2.62	40.16	0.00	6.4%	45.07	7.2%
Distributed system	-\$1.08	\$9.99	39.67	-0.43	6.3%	84.74	13.5%
Enhanced HFC-134a in MACs	-\$175.92	\$16.21	22.69	21.67	3.6%	107.44	17.1%
HFC-152a in MACs	-\$27.59	\$18.18	15.72	0.81	2.5%	123.16	19.6%
Ammonia secondary loop	\$6.33	\$26.40	22.18	-2.71	3.5%	145.34	23.2%
HFC secondary loop	\$4.81	\$26.70	33.20	-0.06	5.3%	178.54	28.5%
CO ₂ for new MACs	\$7.57	\$91.60	17.26	1.83	2.8%	195.80	31.2%

^a Direct reductions refer to HFC emission reductions (off the baseline).

^b Indirect emissions impacts are those associated with energy consumption (not included in the baseline).

4.3 Residential Refrigeration and Air Conditioning

Residential refrigeration includes household refrigerators and freezers (e.g., chest freezers). Air conditioning systems include wall or window mounted air conditioners along with central air conditioning systems. While an exact number of each type of unit is not readily available for Minnesota, nearly every household has at least one combination refrigerator/freezer unit. A majority of homes have some form of air conditioner.

4.3.1 Sector Overview, Analysis and Discussion

According to work published by the EPA, a typical household refrigerator is charged with approximately 0.32 kilograms of refrigerant and has a service life of 20 years.⁸⁴ The units are hermetically sealed and rarely require recharging. As a result, emissions are considered to be very low. In light of the very low leak rate and regulations on refrigerant recycling and reuse and disposal, additional reductions are not considered to be likely. Based on work by Tsai, “Prior to 1990, the majority of domestic refrigerators, freezers and air conditioners use CFC-12 and CFC-11 as working fluids due to their thermodynamic properties, chemical stability, non-flammability and non-toxicity.”⁸⁵ HCFCs have been used as a transitional gas within these systems; however, the use of HCFCs will also be phased out by 2010. HFCs have been the primary replacement gas, typically HFC-134a. Other HFCs are being used including HFC-32, HFC-134, HFC-143, HFC-152a, HFC-227ea, HFC-236ea, HFC-236fa, HFC-245ca and HFC-245fa.

Similar to the refrigeration units described above, most residential air conditioning units are hermetically sealed. According to work conducted by the EPA, the charge size of this type of equipment tends to be between 0.5 to 10 kilograms of refrigerant with a service life of approximately 15 years.⁸⁶ Most air conditioning units will use HCFC-22 for refrigerant until it is phased out in 2010. The replacement refrigerant is likely to be the blend R-410A (Composed of HFC-32(50%) and HFC-125(50%)) with R-707C (HFC-32(23%), HFC-125(25%) and HFC134a (52%)) used in retrofit operations. As noted above, additional analysis is not provided as the units have a very low leak rate due to the hermetically sealed system, along with mandatory refrigerant recycling and reuse during disposal. As a result, additional reductions are not considered to be likely.

4.4 Mobile Air Conditioning

Motor vehicle air conditioners are often referred to as mobile air conditioning or MAC systems. Vehicles older than 1994 used CFC-12 charged air conditioning systems with a charge of between 1 to 1.2 kilograms.⁸⁷ After 1994, MAC systems used HFC-134a almost exclusively, with a charge of around 0.8 kilograms. The expected service life of a MAC unit is approximately 12 years. The units are composed of a number of hoses and joints that connect the compressor to the other air conditioning components and the interior of the automobile. The hoses are considered the primary source of refrigerant leak.

4.4.1 Sector Overview

As noted above, air conditioning systems in automobiles currently use HFC-134a, a high-GWP gas, as the refrigerant. The use of HFC-134a as a refrigerant in MACs replaced CFC-12, which contributed to depletion of the ozone layer and was banned by the Montreal Protocol. Based on typical U.S. driving patterns and conditions, approximately 60% of GHG releases from MACs relate to system energy consumption, 10% relate to transporting the system weight, and about 30% is refrigerant related.⁸⁸ According to the US EPA, MAC refrigerant leakage contributes about 8.7 million metric tons of carbon equivalent to atmospheric emissions of GHGs.

Minnesota implemented a leakage rate reporting requirement for mobile air conditioners (MACs) in 2008 in Minn. Stat. § 216H.11. The reported leakage rates are calculated using a Society of Automotive Engineers' spreadsheet. The method considers the technology of the assembly – such as the type of compressor and the number and type of connections and hoses. From that information, the spreadsheet will calculate the average annual loss of refrigerant from the MAC.

Initial reports were due October 1, 2008. Results for over 360 vehicle models were submitted. The average annual leakage rate reported was 15 grams per year, or about 2.2 percent of the total system charge. Field test results reported in 2006 indicate that the calculated annual average is a reasonable representation of a properly assembled and maintained system. However, the actual leakage amount from any individual vehicle could vary. Individual vehicle leak rates can be found at <http://www.pca.state.mn.us/climatechange/mobileair.html>.

4.4.2 Alternatives

Because of the high global warming potential of HFC-134a and its long atmospheric lifetime, a search for a replacement for it in this application has begun. In addition, the European Union has banned the use of HFC-134a in new automobiles by 2011 and in all vehicles by 2017. Possible substitutes are discussed further in Section 4.4.2.2.

4.4.2.1 Control Technology & Practice

Section 608 of the Clean Air Act prohibits releasing HFC-134a into the atmosphere. The prohibition on venting HFC-134a has been in effect since November 1995. US EPA published a final rule to require recycling of HFC-134a on December 30, 1997, and which became effective on January 29, 1998. Recovery and recycling provides for reuse of the refrigerant once it has been cleaned and purified. Any equipment used to recover or recycle HFC-134a from MAC systems must meet EPA standards and be tested by an approved testing laboratory.

Lutsey⁸⁹ estimates that more efficient MAC systems would reduce CO₂ grams per mile by approximately 1 percent and industry sources note refrigerant losses could be reduced 2-3 percent.⁹⁰ Low leak technology includes multiple o-rings at connections, multiple-lip compressor shaft seals or ultra-low permeability barriers for hoses in contact with the refrigerant.

In its GHG emission standards rule (13 CA ADC § 1961.1), the state of California has proposed an allowance for “low leak air conditioning systems.” Implementation by means of a waiver for this regulation was denied by US EPA. However, that decision is likely to be reconsidered. Eighteen other states and two Canadian provinces have adopted or proposed to adopt the California standard. Implementation of this rule would likely result in reductions in direct emissions of HFC-134a due to leakage from MACs.

4.4.2.2 Substitutes

The options that are being investigated to replace HFC-134a are as follows:

1. Carbon Dioxide (CO₂). This system would use pressurized CO₂ as the coolant. Advantages include the much lower GWP. Disadvantages include CO₂ not being as effective as a coolant and the high operating pressure of the system. Also, using CO₂

as the refrigerant would require a completely different MAC assembly than the existing type.

2. HFC-152a. While chemically similar to HFC-134a, HFC-152 has a much lower GWP and a much shorter atmospheric lifetime. Other advantages include that it is currently available, relatively non-toxic, and has better energy efficiency. Disadvantages include a higher flammability than HFC-134a and that existing MAC assemblies would need to be modified to use it.
3. HFO-1234yf. This compound, under development by DuPont, shows promise. Its performance is similar to HFC-134a and it would be compatible with existing air conditioner assemblies. It has low toxicity and is less flammable than HFC-152. Dupont estimates manufacturing will start in late 2010.

Table #17 - Comparison of Climate Change Characteristics of MAC Refrigerants

Compound	HFC-134a	CO ₂	HFC-152a	HFO-1234yf
GWP	1,430	1	124	4
Atmospheric lifetime	14 years	100 years	1.4 years	11 days

Lutsey² estimates the cost effectiveness of alternative refrigerants at \$56 per tonne CO₂-e (range \$43-\$93) for HFC-152a and \$67 per tonne CO₂-e (range \$52-\$112) for a CO₂ system. In addition, he estimates the potential initial and lifetime cost effectiveness of efficient MAC systems. The initial cost effectiveness range is an estimated savings of approximately \$77-\$113 (2008\$/tonne CO₂-e) and the lifetime cost effectiveness range is an estimated savings of approximately \$73-\$37 (2008\$/tonne CO₂-e).

5.0 Foam Blowing Agents

Polyurethane foam (including foam rubber) is often made by adding small amounts of gases, known as blowing agents, to the mixture. Typically, blowing agents are volatile chemicals that yield important performance characteristics related to thermal insulation. In the early 1990s, the Montreal Protocol led to greatly reduced use of many chlorine-containing blowing agents, such as CFC-11 and to a lesser extent, CFC-12. Other haloalkanes, such as HCFC-141b, were used as interim replacements until their phase out under the IPPC directive on greenhouse gases in 1994 and by the Volatile Organic Compounds (VOC) directive of the EU in 1997. By the late 1990s, the use of blowing agents such as carbon dioxide, pentane, HFC-134a and HFC-245fa became widespread in North America and the EU, although chlorinated blowing agents remain in use in many developing countries.⁹¹

According to the EPA, there are two main types of foams: open cell and closed cell.⁹² The open cell foams have significant leakage of the blowing agent due to the open nature of the cell structure. For the most part, HFCs are not used in this process. Closed cell foams employ HFCs that may release gases as the foam ages, with specific leakage rates a function of foam application and the physical properties of the foam material. The uses of polyurethane foam fall within three categories: thermoset foams, thermoplastic foams and sandwich panels.

The first category of thermoset foams, is created by mixing a blend of two or three chemicals at room temperature and pressure. The mixture reacts, increasing the heat of the mix and the viscosity of the reactants. Eventually, this mixture becomes a solid with gas-filled cells throughout. Within this group of foams, there are five specific types: Polyurethane flexible foams (PU); PU Integral Skin Foams; PU Rigid Foams; One Component Foams (OCF); and Phenolic Foams. Table #18 describes the various forms of thermoset foams and the relationship to product use and blowing agent.

Table #18 – Overview of Foam Type, Product Use and Blowing Agent for Thermoset Foams.

Foam Type	Product Use	Blowing Agent	Comments
Polyurethane flexible foams (PU)	Furniture, bedding automotive interiors, carpet underlay	Non-HFC blowing agent	This sector does not use ozone depleting chemistry or high-global warming potential gases. No further analysis is included.
PU Integral Skin Foams	Seat cushions, back cushions, armrests in automobiles. Also used in shoe soles, flotation devices and skis.	HFC-134a, water blown CO ₂ and HFC-245fa.	Substitutes for HFCs include n-pentane and water-blown CO ₂
PU Rigid Foams	Includes laminate boardstock, appliance insulation, spray insulation, sandwich panels, slabstock and other related foam products.	Historically, CFC-11 and CFC-12 were used. Replaced by HCFCs – with transition out of this blowing agent to lower GWP products.	A number of providers are using the CO ₂ /Water combination with some HFC products. HCFCs still in use.
One Component Foams (OCF)	Products for draft-proofing, sealing doors and window frames and joining insulating panels, roofing boards, and pipe-insulation.	Hydrocarbons are currently used for most OCF production.	Not considered in this analysis.
Phenolic Foams	Excellent fire retardant and thermal insulation properties – used in commercial buildings.	Very little produced in the United States	Not considered in this analysis.

Thermoplastic foams use a plastic resin base that is melted under high temperature and pressure. As the pressure is released from the molten mixture, the blowing agent and consequently the mixture, expands. The foaming material is then forced through a small die opening, creating a continuous board of desired thickness. The foams manufactured through this process include polyolefin, expanded polystyrene (EPS), extruded polystyrene (XPS) sheet, and XPS boardstock applications. Table #19 provides information on the non-HFC blowing agents that are applicable to this sector.⁹³

Table #19 - Overview of Foam Type, Product Use and Blowing Agent for Thermoplastic Foams.

Thermoplastic Foams			
Foam Type	Product Use	Blowing Agent	Comments
Polyolefin Foam	Pipewrap insulation, construction materials, protective packaging, flotation devices, and automotive bumper systems.	Variety of HFCs, hydrocarbons and liquid carbon dioxide (LCDs) used as blowing agents.	Options include the installation of regenerative thermal oxidizers and partially substitute ethane for isobutene.
XPS Sheet	Food service and food packaging products, protective packaging for furniture and electronics.	Hydrocarbons and to a much lesser extent – HFC-152a.	Not considered in this analysis.
XPS Boardstock	Foams used in insulation of roofs, floors, walls, tile and plaster backing applications – also used as core material for sandwich panel construction and specialty applications.	HCFC agents are used as the primary blowing agent. Some alternatives are being used.	Not considered in this analysis.
XPS Foam	Steam molded sheets.	Process did not use CFCs – some HFC use is possible.	Not considered in this analysis.

The third category is the sandwich panel product. Sandwich panels consist of foam cores between rigid facings. The primary benefit of these products is their insulating and self-adhesive values. They are typically used in various appliances including doors, panels, water heaters, cold storage, and in the transport industry for insulated trucks and refrigerated transports. The industry currently uses HCFCs, water-blown CO₂, hydrocarbons and various blended agents. According to work by the EPA, the likely blowing agents used in this application after 2010 will be various types of HFCs, CO₂/water, LCD, and blended agents.⁹⁴ Other factors that must be considered include fire protection and dimensional stability.

5.1 Sector Overview

Based on MPCA air quality permit data, there are approximately 52 industrial facilities in the state that employ some form of blowing agent into their foam process. This information does not include the foam insulators that may use HFCs or PFCs. The overall number of foam insulators in the state is not currently available. Business-as-usual baseline emissions for foams in the United States were estimated to be 0.3 MtCO₂eq in 2000, 5.7 MtCO₂eq in 2010 and 11.3 MtCO₂eq in 2020.⁹⁵ Minnesota's contribution to the national baseline emission data is not presently known. The information provided in Table #20 presents specific emission releases (as a percent) through a lifecycle analysis (i.e., manufacturing to disposal).

Table #20 – EPA’s Vintaging Model Emissions for Foams’ End Uses (EPA, 2008).

Foams End-Use	Loss at manufacturing (%)	Annual release rate (%)	Release lifetime (Years)	Loss at disposal (%)	Total released (%)
Flexible PU	100.0%	0.000%	1	0.00%	100.0%
Polyisocyanurate boardstock	6.0%	1.000%	50	44.00%	100.0%
Rigid PU integral skin	95.0%	2.500%	2	0.00%	100.0%
PU appliance	4.0%	0.250%	20	27.30% ^a	36.3% ^b
PU commercial refrigeration	6.0%	0.250%	15	90.25%	100.0%
PU spray	15.0%	1.500%	56	1.00%	100.0%
One component	100.0%	0.000%	1	0.00%	100.0%
PU slabstock and other	37.5%	0.750%	15	51.25%	100.0%
Phenolic	23.0%	0.875%	32	49.00%	100.0%
Polyolefin	95.0%	2.500%	2	0.00%	100.0%
XPS foam sheet	40.0%	2.00%	25	0.00%	90.0%
XPS boardstock	25.0%	0.750%	50	37.50%	100.0%
Sandwich panel	5.5%	0.500%	50	69.50%	100.0%

^a Estimated as 30 percent of the blowing agent remaining in the foam at the time of disposal

^b Emissions from disposed products may continue if not otherwise abated. For HFCs, this analysis assumes 2 percent of the total blowing agent used will continue to be emitted every year after disposal.

The emission data presented in Table #20 was generated using EPA’s Vintaging model, rather than specific emission measurement techniques.

5.2 Alternatives

There are a variety of approaches that can be used to reduce total greenhouse gas emissions from foam blowing operations. The categories include non-HFC blowing agents, use of lower GWP HFCs, alternative insulation technologies and direct emission reduction.

5.2.1 Non-HFC Blowing Agents

The non-HFC blowing agents include hydrocarbons (HC), LCD and water-blown (in situ) carbon dioxide (CO₂/water). Section 612 of the CAA (known as "SNAP" because of the title "Significant New Applications Program") has approved a variety of HCs as replacement for HFCs that include propane, butane, isobutene, n-pentane, isopentane, cyclopentane, and isomers of hexane. Three factors are relevant to the use of HCs as a substitute. First is the issue of flammability. A facility converting to an HC blowing agent may have to modify the facility to account for fire hazards, incur additional costs for training and may be required to use greater amounts or different types of fire retardant. HCs are volatile organic compounds (VOCs), and are contributors to ground-level ozone and smog. This characteristic provides another layer of regulation under the CAA. In some places of the United States, where compliance with the National Ambient Air Quality Standards is an issue, HCs may not be used without emission control technology, adding further cost to the transition. Lastly, there are performance issues associated with the use of HCs. According the EPA, HCs yield approximately 85% of the insulating value of HCFCs. One resolution to this issue is to produce a thicker product; however, this practice will increase the unit cost. This approach is not viable in situations where the product is of a fixed thickness.

To use LCD may require new formulations for the gas to dissolve more readily. Metering equipment used to dose formulations with CO₂ has not been reliable. There has been some concern for limited solubility, homogeneity of the chemical mix, ability to control the decompression and the distribution of the froth. Some additional concerns include lower thermal conductivity, lower dimensional stability, and higher density in comparison to foams blown with HCFC. The EPA noted that these limitations can be addressed through blending CO₂ with hydrocarbons or HFCs.⁹⁶

The water-blown carbon dioxide process is produced from a chemical reaction between water and a chemical known as polymeric isocyanate. As an isocyanate, toxicity is a potential concern^{viii}, though there are reportedly very few occupational health and safety issues if handled properly.⁹⁷ The use of this process does have similar limitations to that found in LCD. For foams that must be water-proof, this process has been a challenge as the foam products contain an increased percentage of open cell content. This condition affects the water-proofing properties of the foam. In addition, this process often requires higher concentrations of polymeric isocyanate. This is a limitation for some production equipment; however, blending HFCs with this process will overcome this issue.⁹⁸ One benefit of this approach is that it requires less mechanical modification to convert production lines over to this approach in comparison to LCD. In addition, the final CO₂ content and overall foam properties are more consistent than the LCD counterparts.

5.2.2 Lower-GWP HFC Substitution

Manufacturers can elect to abandon the use of an HFC with a high-GWP for one with a lower GWP. This practice results in a smaller carbon footprint, but may require additional energy penalties. The factors affecting the choice of a blowing agent are a function of performance and economics. The performance factors may include utility, functionality, solubility and vapor pressure tolerance. Consideration is given for the product type, manufacturing process and specific end use. Cost underlies all of these factors. This is typically a case-by-case analysis and will not be presented further in this report beyond this discussion.

5.2.3 Alternative Insulation Materials and Technology

A variety of insulation technologies exist that can be used in place of foam products. The EPA has identified various types of fiberboard, fiber and cellular glass, as alternative insulation materials.⁹⁹ The Department of Energy has also identified alternative insulation materials including natural fibers and related materials.¹⁰⁰

5.2.4 Direct Emission Reduction

A direct emission reduction approach is the capture of emissions during the foam production process. This alternative is specific to the production method and design. A variety of techniques exist that could be implemented into the production process. The control technologies include combustion or treatment of pollutants. As each technology is specific to the various production methods, additional analysis will not be provided on these activities.

^{viii} Based on toxicological literature, the reactivity of isocyanates makes them harmful to living tissue. They are toxic and are known to cause asthma in humans, both through inhalation exposure and dermal contact. Exposure to isocyanates and their vapors should be avoided.

5.5 Cost Evaluation

The MPCA did not conduct a specific cost effectiveness analysis for this sector in light of a paucity of data specific to the industry and emissions. The MPCA relied upon the EPA analysis conducted for this sector that employed a discounted cash-flow analysis use to estimate a break-even carbon price in dollars per metric ton of carbon equivalent (TCE).¹⁰¹ An economic cost effectiveness model was used to determine the net present value for the transition to a non-HFC alternative based on annual cash flows, start-up capital costs, annual variable costs, annual indirect costs, and annual revenue from the sale of emission reduction credits.¹⁰²

The emissions used by the EPA in this analysis were developed using a Life Cycle Climate Performance (LCCP) approach. The EPA analysis accounted for the following:

- HFC emission reductions from blowing-agent substitutions;
- Indirect emissions of CO₂ associated with energy efficiency differences resulting from the substitution (unless otherwise stated), and;
- Embodied energy and fugitive emissions from the manufacture of the HFC.

The EPA based the cost information on incremental differences between using HFCs and switching to non-HFCs. The information considered in this analysis included the following costs (Table #21):

Table #21 – Description of Cost Parameters used in the Life Cycle Climate Performance for Blowing Agents

Costs	Description
Capital Cost	Capital costs account for equipment costs to modify existing plants and to maintain production capacity.
Blowing Agent Cost	This cost addresses the difference between costs and quantity of the HFC and non-HFC alternative required.
Foam Cost	This cost addresses changes in foam density, the amount of fire retardant used, the quantity and type of polyol, etc..
Test & Training Cost	These are costs associated with transitioning to non-HFC alternatives.
Indirect Costs	This includes energy efficiency differences unless otherwise noted.

One of the features of the important transition features not accounted for in the analysis was the learning curve that accompanies new production methods and production consistency. This type of information is specific to the production method and was not employed by EPA for their analysis.

The paucity of financial information resulted in the analysis of only two foam production types: PU spray foam and PU appliance foams. A summary of the cost effective analysis is included in Table #22:

Table #22 – A summary of EPA Cost Effectiveness Analysis for various HFC Reduction Options.

Option	Cost (\$/TCE) and Discount Rate (%)		Incremental Reductions		Sum of Reductions	
	4%	8%	MMTCE	% of baseline emissions	MMTCE	% of baseline emissions
PU Spray Foams – Replace HFC-245fa/CO ₂ (water) with hydrocarbons	(15.70)	(15.64)	0.5	35%	0.5	35%
PU Appliance Foams – Replace HFC-134a with cyclopentane	17.18	43.25	0.03	2%	0.53	37%
PU Spray Foams – Replace HFC-245fa/CO ₂ (water) with CO ₂ (water)	114.09	123.52	0.5	35%	1.03	72%

Based on the EPA analysis, a hypothetical transition to non-HFC alternatives would result in a total reduction of 1.03 MMTCE or 72% of the 2010 baseline estimates from the foam sector.¹⁰³ This evaluation reflects national, rather than Minnesota data. The analysis is instructive in illustrating potential reductions through the application of the alternatives identified by the EPA. Emissions of HFCs from this sector are expected to rise in the United States due to the replacement of CFCs and HCFCs under the Montreal Protocol.

The 2008 EPA analysis provided a global breakeven cost analysis that addressed many of the control options and strategies reviewed in the 2001 study. A summary of this evaluation is found in Table #23. Many of the reduction options appear to have merit. However, site specific considerations will be important in determining the overall cost effectiveness.

Table #23 – World breakeven costs and emissions reduction in 2020 for foams (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction of option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
XPS boardstock: HFC-134a/CO ₂ (LCD) – based blends to CO ₂ (LCD)/alcohol	-\$7.81	-\$7.81	2.49	8.7%	2.49	8.7%
PU Spray: HFC-245fa/CO ₂ (water) to HC	-\$5.19	-\$2.91	1.59	5.5%	4.08	14.2%
PU one-compartment HFC-134a to HC	-\$1.76	-\$1.76	0.48	1.7%	4.56	15.9%
PU one-compartment HFC-152a to HC	-\$0.15	-\$0.15	0.06	0.2%	4.62	16.1%
PU continuous and discontinuous: HFC-134a to HC	\$0.86	\$0.86	0.92	3.2%	5.54	19.3%
PU appliance: automated process with foam grinding, HFC adsorption, and foam landfilling	\$36.07	\$36.07	0.01	0.0%	5.55	19.4%
PU spray: HFC-245fa/CO ₂ (water) to CO ₂ (water)	\$41.84	\$41.84	1.42	5.0%	6.98	24.4%
PU appliance: HFC-134a to HC	\$42.06	\$42.06	0.17	0.6%	7.14	24.9%
PU appliance: manual process with foam incineration	\$82.54	\$82.54	0.04	0.1%	7.18	25.1%
PU appliance: HFC-245fa to HC	\$192.54	\$192.54	1.62	5.7%	8.81	30.7%

6.0 Fire Protection

There are functionally two types of fire suppression systems. The first is the portable fire extinguisher. These systems originally used Halon 1211. The second is the total flooding applications used in a variety of facilities. These systems used Halon 1301.

Portable fire extinguishers are used in nearly every business, including manufacturing and retail operations. Many homes employ portable fire extinguishers as part of their home fire protection strategy. The EPA noted in 2001 that approximately 80% of new portable fire extinguishers are manufactured with non-ozone depleting and low GWP alternatives such as HCFC blends, dry powder, carbon dioxide, or water.¹⁰⁴ HFC and PFC products are not likely to be substantial replacements in this market.

Prior to the Montreal protocol, halons and CFCs were the primary choices for fixed, total flooding fire suppression systems. Typically, these systems are used to protect high-value electronics. Halons and CFCs for fire suppression have been phased out of use in developed countries since December 31, 1991. Both PFCs and HFCs have been used as replacement gases. HFCs have been used "...because they possess desirable properties [of] electrical non-conductivity, ready vaporization, low toxicity, and non-flammability."¹⁰⁵ The HFCs used in fire suppression include HFC-23, HFC-125, HFC-236fa and HFC-227ea.

The EPA identified the following applications for total flooding fire suppression systems:¹⁰⁶

- High value electronic and telecommunications equipment
- Military applications
- Oil production facilities
- Flammable liquid storage areas
- Engine nacelles and cargo bays of commercial aircraft
- Cultural institutions and museums
- Records storage areas
- Bank vaults
- Warehouses
- Laboratories, research centers and high-security military facilities.

Total flooding suppression systems (TFSS) are designed for specific spaces and needs. Typically, a TFSS is subject to regulation through a variety of public sector codes, insurance company policies, the National Fire Protection Association (NFPA), factory installation criteria, and the International Organization for Standardization (ISO). A standard TFSS utilizes a system of pressurized tanks that are designed and installed consistent with NFPA standards.^{ix} This standard illustrates the type of fire suppression agents that can be used in TFSS applications. The fire suppression materials are known as "clean agents" and must be electrically nonconductive, volatile, or gaseous fire suppression agents that do not leave a residue after evaporation.^x This is

^{ix} Retrieved from <http://www.nfpa.org/index.asp?cookie%5Ftest=1> on December 18, 2008.

^x Volatility should not be confused with flammability. Volatility refers to the property of a substance to transition from either a liquid or solid to a gaseous state. This is a preferable characteristic for TFSS fire suppressants that are released as liquids. The evaporation of water is a demonstration of volatility. Highly volatile fire suppressants will volatilize into the atmosphere, thereby reducing or eliminating potential "water" damage to the inventory.

a critical characteristic as high-value items may be saved from a fire, only to be destroyed by the fire suppressant.

Each TFSS is effectively designed around the clean agent to ensure that in the event of a fire, the suppressant canisters can be emptied within ten seconds, consistent with NFPA standards. This means that the piping distribution system and nozzles are specific to the clean agent, making substitution more complicated. Once a TFSS is operated, the system is no longer operative and must be overhauled to return to an operative condition. This is typically the only time that the fire suppressant is released into the environment.

Each fire suppression system must be designed to account for a specific fire potential. The NFPA has classified fires into five different classifications, listed in Table #24:

Table #24 – NFPA Classification of Fires

Class	Description
Class A	Class A fires are ordinary materials like burning paper, lumber, cardboard, plastics etc.
Class B	Class B fires involve flammable or combustible liquids such as gasoline, kerosene, and common organic solvents used in the laboratory.
Class C	Class C fires involve energized electrical equipment, such as appliances, switches, panel boxes, power tools, hot plates and stirrers. Water can be a dangerous extinguishing medium for class C fires because of the risk of electrical shock unless a specialized water mist extinguisher is used.
Class D	Class D fires involve combustible metals, such as magnesium, titanium, potassium and sodium as well as pyrophoric organometallic reagents such as alkyllithiums, Grignards and diethylzinc. These materials burn at high temperatures and will react violently with water, air, and/or other chemicals.
Class K	Class K fires are kitchen fires. This class was added to the NFPA portable extinguishers Standard 10 in 1998. Kitchen extinguishers installed before June 30, 1998 are "grandfathered" into the standard.

A fire suppression system may need to account for various classifications of fires (e.g., a Class A,B and C fire within a single space). This is another complication in selecting a potential substitute fire suppression agent.

Halons are being phased out under the Montreal Protocol. Replacements have included inert gases such as combinations of nitrogen, argon and carbon dioxide, along with HFCs and in limited circumstances, PFCs. New clean agent substitutes have been developed with non-ozone depleting and non-GWP properties. The EPA noted that not-in-kind alternative technologies are also available, including powdered aerosols, water sprinkles, water mist systems and foams.¹⁰⁷

6.1 Sector Overview

The total number of fire extinguishers in the state is not accurately known. Based on available information, there are approximately 20,000 TFSS in the state.^{xi} There are a wide range of fire suppression agents used in both systems. The content reflects the specific use and the age of the system. According to the 2008 EPA report, the total baseline emissions of HFCs from fire extinguishers in 2000 was 0.7 MtCO₂eq, in 2010, it is predicted to be 1.6 MtCO₂eq, with the 2020 predicted amount to be 1.9 MtCO₂eq.¹⁰⁸

^{xi} Personal communication with Tom Nardini` Nardini Fire Equipment – January 6, 2009.

6.2 Alternatives

The alternatives identified within this sector include the use of substitute clean agents for fire suppression and alternative technologies and practices. Each of these approaches has potential for application within the sector. The following is a discussion of each approach.

6.2.1 Substitute Fire Suppression Agents

The substitute fire suppression agents identified for the analysis included carbon dioxide, inert gases, water mist systems and two engineered products generically known as fluorinated ketones (FK-5-1-12). According to the EPA, carbon dioxide is used in TFSS technology; however, in light of the concentrations required to suppress a fire (at least 34%), human health is a concern as the concentrations are considered lethal.¹⁰⁹ As a result, the use of carbon dioxide is highly regulated in occupied areas.

6.2.2 Alternative Technologies & Practices

Based on work by EPA, two types of alternative practices appear to be viable for TFSS: early fire detection methods and controlled discharge systems.¹¹⁰ Early fire detection systems are considered to be an effective means of reducing HFC and PFC emissions by determining the difference between real fires and false alarms, and also by addressing fires early enough, potentially eliminating the need to utilize HFC and/or PFC fire suppression products. Several products are available commercially that are integrated into TFSS technology.

Another form of early detection is the use of infrared cameras. More specifically, this technology is referred to as a thermographic camera. It is also referred to as Forward Looking InfraRed Technology (FLIRT). This technology forms an image using infrared radiation, similar to a common camera that forms an image using visible light.

All objects emit a certain amount of radiation as a function of their temperatures. Generally speaking, the higher an object's temperature is, the more infrared or heat radiation it emits. A thermographic camera can detect this radiation. This is particularly useful in the early detection of fires, where heat profiles change rapidly. Even small changes in heat profiles are detectable with this type of technology. One of the attractive features of this approach is that it works in total darkness as visible light level does not matter.

Another possible feature is the use of controlled discharges of fire suppression agents, rather than a complete discharge of the total load of fire suppression agent. The manner of control with TFSS technology is dictated in part by regulations and the type of fire suppression agent being used. With portable fire extinguishers, training on proper use affects the quantity of fire suppression agent used to extinguish a blaze.

6.3 Cost Analysis

The cost analysis was conducted by EPA using the Vintaging model and only accounts for TFSS technology. The baseline utilized for this analysis is a combination of portable fire extinguishers and the TFSS technology. The emissions do not distinguish between the emissions from servicing, accidental discharge, false alarms, leaks or actual fire-response discharges. Based on the information provided by EPA, it was expected that 80% of the predicted 2010 baseline emissions were from TFSS technology with the remaining 20% comprised of portable fire extinguishers.

The EPA selected three options for this analysis: water mist and inert gas systems (See Table #25). The inert gas system was evaluated using a zero-GWP substitute. According to the EPA, inert gas accounts for approximately 95% of the overall TFSS sector.¹¹¹ The use of an inert gas (e.g., Sapphire[®] or Inergen[®]) was estimated to displace approximately 45% of HFC use at the time of the analysis in 2000. During the time that the EPA conducted the analysis, it was assumed that the cost of the inert gas substitute system was 10% higher than the existing approach. This was in part related to the greater storage needs for an increased volume of inert gas in comparison to the baseline gas used in the analysis (HFC-227ea). The economics of this analysis, conducted in 2000, may no longer be relevant in light of new inert gas substitutes.

Table #25 – World Breakeven Costs and Emissions Reduction in 2020 for Fire Extinguishing (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Direct Emissions Reduction (MtCO ₂ eq)	Indirect Emissions Reduction (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High					
	FK-5-1-12	\$37.36					
Inert gases	\$34.53	\$48.85	1.58	-0.11	11.5%	3.55	25.9%
Water mist	\$48.16	\$82.40	0.23	-0.04	1.6%	3.77	27.6%

^a Direct reductions refer to HFC emission reductions (off the baseline).

^b Indirect emissions impacts are those associated with energy consumption (not included in the baseline).

The water mist system is functional for Class B fire hazards and in situations where the operational temperatures are not below freezing. At the time that the EPA conducted the 2001 analysis; the implementation cost for a water mist system was 75% of a comparable HFC system and would be able to replace 5% of the existing TFSS technology.

The use of HFCs as TFSS fire suppression systems is expected to rise as HCFCs are phased out in 2010 under the Montreal Protocol. The site-specific character of TFSS fire suppression systems creates situations for unique costs of installation. Each of the three alternatives are viable depending on the nature of use.

7.0 Semiconductor Manufacture

Semiconductors are the foundation of electronic technology. A semiconductor is typically a solid material that is a combination of electrical properties that include both conductivity and insulator. This composition can be highly variable and operate over a range that is either permanent (specific conductivity) or dynamic (variable conductivity). Semiconductors are used in a variety of devices including computers, mobile phones, and digital audio players. Silicon is the primary component used to create most semiconductors, however; many other materials, including precious metals and engineered gases, are used in the development of the product.

7.2 Sector Overview

Minnesota currently has six operating semiconductor manufacturing facilities. The semiconductor operations in Minnesota produce computer chips for a variety of uses including automobiles, video game systems and computers. The MPCA received five high-GWP purchase reports from the six operating facilities in the state. The EPA noted that the baseline emissions of PFCs (including SF₆) were 6.4 MtCO₂eq in 2000, 28.2 MtCO₂eq in 2010 and 46.1 MtCO₂eq in 2020.¹¹² With a technology adoption baseline, the emissions drop substantially. Under this analysis, the 2000 annual emissions were predicted to be 6.4 MtCO₂eq, with a predicted 5.5 MtCO₂eq in 2010 and 4.1 MtCO₂eq in 2020.¹¹³

7.3 Alternatives and Substitutes for the Semiconductor Manufacturing Industry

The creation of a semiconductor involves a number of activities designed to laminate and deposit various materials that ultimately results in the development of a computer chip or circuit. Fluorinated engineered gases are a minor component of the semiconductor development process. A variety of HFCs, PFCs, and SF₆ are used in semiconductor manufacture. The engineered gases most commonly used include HFC-23, CF₄, C₂F₆, SF₆, NF₃, C₃F₈, and C-C₄F₈ (also referred to as C₄F₈). While the gases used within the industry are fairly consistent, the combinations and concentrations vary from producer to producer. The EPA conducted this analysis based on the sales of four main gases (HFC-23, CF₄, C₂F₆, SF₆) to semiconductor firms. The analysis also included options to replace NF₃. While the semiconductor manufacturing process is highly complex, the EPA identified the following areas to reduce emissions of high-GWP gases: Chemical Vapor Deposition (CVD) cleaning emission reduction technologies; Etching emission reduction technologies; and, Facility-wide solutions.

7.3.1 CVD Cleaning Emission Reduction Technologies

The chemical vapor deposition process can be defined as "...the deposition of a solid on a heated surface from a chemical reaction in the vapor phase."¹¹⁴ The CVD process is widely used in the semiconductor industry to deposit a variety of thin film materials. It is a key component of the semiconductor manufacturing process, often involving lengthy and complicated procedures to develop a variety of thin-film layers on the semiconductor.

To manufacture effective semiconductors, defects must be minimized. Throughout the CVD chamber, deposition debris accumulates. The debris can cause defects within the semiconductor product. In order to abate this concern, a cleaning gas is used to remove deposition debris. A number of PFC gases have been used in this process including CF₄, C₂F₆, and C₃F₈.¹¹⁵

Based on recent work, iodofluorocarbons appear to be potential replacement for conventional PFCs.¹¹⁶ Reportedly, the atmospheric lifetime is less than one day. The authors of this work

indicated that they had "...successfully demonstrated the use of CF₃/O₂ mixtures to etch silicon oxide and nitride films in a PECVD batch reactor."¹¹⁷

A Subcommittee of the National Academy of Science reviewed the potential toxicity of CF₃I, including genotoxicity, carcinogenicity, reproductive toxicity, cardiac sensitization, various pharmacokinetic models and human exposure scenarios.¹¹⁸ The Subcommittee recommended that there was no further need for evaluation of acute, subacute or subchronic testing of CF₃I, but noted some concern on studies investigating the genotoxicity and also noted that short-term carcinogenicity testing be conducted to further evaluate potential cancer risks. There does not appear to be any reproductive issues associated with the use of CF₃I, but some concern was expressed over the results of cardiac arrhythmia in animals.

As previously noted, C₂F₆ has been one of the primary dry chamber cleaning gases. The EPA conducted a cost effectiveness evaluation using the Vintaging model and assessed the use of NF₃ as a substitute. NF₃ has a high-GWP (8,000 v. 9,200), however, it is considered to be a more efficient product (meaning less of the gas is used) that leads to a reduced climate impact in comparison to C₂F₆. The EPA evaluated two techniques using NF₃ as a cleaning gas: *in situ* NF₃ Clean Technology and NF₃ Remote CleanTM Technology.

The NF₃ Clean Technology has demonstrated emission reductions of greater than 90 percent at all process conditions. The EPA noted that the Remote CleanTM Technology is capable of reducing emissions by over 95 percent, with a chamber cleaning time of 30 to 50 percent faster than baseline C₂F₆ cleaning times.¹¹⁹

7.3.2 Etching Emission Reduction Technologies

Etching in the semiconductor industry refers to both wet and dry etching. This discussion focuses on dry etching, as this process employs high-GWP gases. Dry etching in the semiconductor manufacturing sector refers to the dry etching process where material is removed in a masked pattern by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons, oxygen, chlorine, boron trichloride; sometimes with addition of nitrogen, argon, helium and other gases). The focused bombardment dislodges portions of the material from the exposed surface of the semiconductor. The etching process is used to attack certain areas of a semiconductor surface in order to form contact holes (to the underlying semiconductor substrate) or via holes (created to provide an interconnect path between conductive layers in the layered semiconductor device) or to otherwise remove portions of semiconductor layers where predominantly vertical sides are desired.

The EPA assessed three emission reduction approaches: Point-of-Use (POU) Plasma Abatement; Thermal Destruction/Thermal Processing Units; and the Catalytic Decomposition System.

According to the resources reviewed, the two most widely used plasma technologies are the Litmas "Blue" and "Red", and AMAT's PegasysTM POU unit. Both of these approaches are well developed and commercialized within the semiconductor manufacturing industry. Based on work by IEA, Litmas reported emission reductions from 97% to 99% for its "Blue" POU device; AMAT's capacity coupled device (Pegasys IITM) claims typically more than 95% reduction in emissions.¹²⁰ According to the EPA, this option has been demonstrated to attain the reduction efficiency of more than 97% when water vapor is used as an additive gas.¹²¹ Based on discussions with a local semiconductor manufacturer, cost is an issue.^{xii} There is currently only

^{xii} Comments provided by Rosanna Imholte, PolarFab Semiconductor, Bloomington, Minnesota, January 8, 2009.

one AMAT PFC abatement unit in use in the U.S (Intel). Most semiconductor companies have elected not to install them due to their high upfront cost (as much as five times the cost of scrubbers) and the high cost of operation and maintenance.

Thermal destruction technology can be used within the semiconductor manufacturing process to reduce PFCs emissions from both the CVD chamber cleaning and etching processes. The thermal destruction system is installed downstream of the process tool so that it does not affect the manufacturing process performance. The high-GWP emissions are oxidized in a natural gas-fired burner prior to the removal of the combustion products by the waste treatment systems. According to the information reviewed, the burner system requires pretreatment of inlet streams to reduce the loads of unused deposition/etchant gases and particles that can block the system.¹²² Hydrofluoric acid formed in thermal destruction systems may be removed via POU scrubbers to prevent exceeding scrubber design limits.¹²³ Based on a review of this technology by the state of California, the Edwards TPU 4214 (oxidation with advanced burner technology) is applicable for all high-GWP emissions and achieves more than 99% destruction efficiency. Several PFC thermal destruction systems can effectively abate some PFCs, but only a few have been proven to abate all PFCs at greater than 90% destruction efficiency.¹²⁴ According to the United States Climate Change Technology program, several PFC thermal destruction systems are commercially available, but the Edwards TPU 4214 is the only thermal-destruction device in commercial use and represents a favored POU solution for chemical vapor deposition cleaning processes.¹²⁵ One of the concerns noted with this approach is that the thermal destruction system requires a combustion fuel and uses significant amounts of cooling water, creating an additional waste stream, along with producing NOx emissions that are regulated air pollutants.¹²⁶

The Catalytic Decomposition System (Hitachi) is applicable to CF₄, C₂F₆, C₄F₈, and SF₆. Reduction efficiency of this technological option is more than 99% for each gas.¹²⁷ This technology has been adopted by fabrications almost exclusively outside the United States.¹²⁸

There are several technical limitations with this approach. According to work by the state of California, catalytic systems require pretreatment of inlet streams to reduce the loads of unused deposition/etchant gases and particles that can block burners or clog catalysts.¹²⁹ In light of the variability within processes and the nature of operations, the design must reflect a minimum concentration and flow of PFC within the exhaust stream. To that end, off-the-shelf systems can be applied only for facilities with certain stream or process specifications.¹³⁰

7.3.3 Facility-Wide Solutions

Facility-wide solutions include the use of substitutes, capture/recovery technology and process optimization. A wide variety of gas substitutes could be used to replace high-GWP gases in semiconductor manufacturing process. The EPA noted that in the etching process, one gas used in the process, C-C₄F₈, has a GWP of 8,700 years. While it is typically less than one percent of the gases used in the process, alternatives such as C₃F₆ and C₅F₈ create approximately equal contact holes and have much lower GWPs (90 and 100 respectively). According to work by Cowles (1999) and Hokari (1999), C₅F₈ has an atmospheric lifetime of one year and based on the nature of the control technology, a destruction efficiency of greater than 90 percent.¹³¹ The EPA noted that there may also be improved etching performance that results in the use of less etchant during the manufacturing process. The EPA did not conduct a thorough cost analysis within the context of substitutes due to lack availability at the time of the analysis.

Capturing or recovering PFCs is yet another practice that can be employed to reduce emissions from the manufacture of semiconductors. This technology separates unreacted or process-generated fluorocarbons (FCs) from other gases used in the processing. During the time that EPA conducted their analysis in 2000, capture systems were readily available and capable of a 90 percent emission removal rate. The removal efficiency has been reported at around 90 percent for CF₄, C₂F₆, C₃F₈, and SF₆, but lower for CHF₃ and NF₃ (between 50 to 60 percent).¹³² There is some possibility for gas recycling through the use of this technology.¹³³ However, it may be a limitation with NF₃ cleaning systems. NF₃ cleaning systems create an effluent that is deficient in recoverable FC gas, making economic recovery difficult to impossible.

Lastly, the semiconductor industry is able to employ a variety of process optimization techniques. The goal of optimization within the context of semiconductor manufacturing is the use of FC. By optimizing consumption of FC gas during manufacturing, excess gas are not generated – thereby reducing emissions. This approach is conducted on a case-by-case analysis. Cost estimates for this practice are highly variable and dependent upon a variety factors beyond the scope of this analysis.

7.4 Cost Evaluation

A major factor within this sector is the global nature of the semiconductor industry. The EPA noted that the costs of equipment and operation are not expected to differ greatly between operations in part due to the global nature of the semiconductor industry. The abatement strategies for the semiconductor manufacturing industry presented previously were evaluated in context to the baseline analysis for this sector (no-action and technology adoption analysis). For each curve, the control cost in 2010 appears to be about \$30, while in 2020, the control cost is approximately \$15.¹³⁴ The information in Table #26 provides a summary of the emission reductions and costs in 2020 for a no-action baseline.

Table #26 – National Emission Reduction and Costs in 2020 – No Action Baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
Remote clean	-\$67.06	-\$67.06	126.1	54.4%	126.1	54.4%
C ₃ F ₈ replacement	\$0.00	\$0.00	7.9	3.4%	134.0	57.8%
Capture/recovery (membrane)	\$4.96	\$4.96	26.4	11.4%	160.4	69.2%
Plasma abatement (etch)	\$16.83	\$16.83	31.5	13.6%	191.9	82.8%
Thermal abatement	\$24.34	\$24.34	12.7	5.5%	204.6	88.2%
Catalytic abatement	\$33.17	\$33.17	13.7	5.9%	218.2	94.1%

A similar presentation is provided in Table #27. The analysis in Table #27 presents a technology adoption baseline. The running sum of reductions is an order of magnitude less under the technology adoption baseline. This is due to the incremental reductions that occurred due to the implementation of voluntary industry controls.

Table #27 – National Emission Reduction and Costs in 2020 – Technology Adoption Baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
Remote clean	-\$67.06	-\$67.06	13.6	41.7%	11.8	41.7%
C ₃ F ₈ replacement	\$0.00	\$0.00	0.8	2.5%	12.5	44.2%
Capture/recovery (membrane)	\$4.96	\$4.96	0.4	0.0%	12.5	44.2%
Plasma abatement (etch)	\$16.83	\$16.83	2.8	6.3%	14.3	50.5%
Thermal abatement	\$24.34	\$24.34	0.7	0.6%	14.5	51.1%
Catalytic abatement	\$33.17	\$33.17	0.7	0.0%	14.5	51.1%

Table #28 – Options and Cost Relationships to Emission Reduction Identified by EPA (2001).

Option	Cost and Emission Reduction Comments
NF ₃ Remote Clean/ NF ₃ <i>In Situ</i> Clean	<ul style="list-style-type: none"> Total costs equal approximately \$95,000 per tool per year, which includes capital and operations/maintenance (O&M) costs; and emission reductions are estimated to be 5,500 metric tons of carbon equivalent (TCE). The remote clean technology uses approximately 1,400 pounds of NF₃/year, with an emission factor of approximately one percent (GWP 8,000). The business-as-usual cleaning technology would require approximately five times the amount of material by weight, thus replacing approximately 7,000 pounds of C₂F₆/year, with an emission factor of 70 percent (GWP 9,200).
Point of Use Plasma Abatement	<p>The cost and emission reduction estimates for plasma abatement systems assume four chambers per tool and one tool. The costs and emissions reductions are as follows:</p> <ul style="list-style-type: none"> Total costs equal approximately \$24,000 per year, which includes capital, O&M, and installation costs; Emission reductions are estimated to be 621 TCE. To estimate the potential reduction, it was assumed that C₂F₆ has a flow of 100 cubic centimeters per minute; and An emission reduction of 261 kilograms per year per tool is expected based on the tool running for 650 hours/year with an abatement efficiency of 97 percent.
Thermal Destruction System	<p>The cost and emission reduction estimates presented here assume 10 systems per facility. The costs and emission reductions are as follows:</p> <ul style="list-style-type: none"> Total costs equal approximately \$2.1 to \$3.1 million per year, which includes capital, O&M, and installation costs; and Emission reductions are estimated to be 22,000 to 60,000 TCE.
PFC Capture/Recovery or Recycling System	<p>The cost estimate and emission reduction potential of this technology were based on the following assumptions:</p> <ul style="list-style-type: none"> Total costs equal approximately \$1.8 million per year, which includes capital, O&M, and installation costs for two units per facility. Installation costs can vary considerably. One major cost is the installation cost for providing a segregated FC waste stream. For a new fabrication facility, this could range between \$600,000 to \$1,000,000, but could be much more for an older large facility; Emission reductions are estimated to be 50,000 to 134,000 TCE; Destruction costs are estimated to be \$3/kilogram or approximately \$1.10/TCE; Two systems are needed per facility; and It is assumed that FC recapture systems could be installed to accommodate up to half of all emissions from semiconductor manufacture. Thus, given the 90 percent average removal rate, up to 45 percent of emissions could be eliminated using FC recapture systems. Similarly, 45 percent could be eliminated by the destruction systems described above. These two options are mutually exclusive; manufacturers would implement either one or the other because using thermal destruction does not leave enough FCs in the stream to make recapture economically viable. The emission reductions estimated to be attainable from each option cannot be added together.

The EPA conducted a market share analysis in order to better predict the market penetration of the control options presented above. This analysis was conducted in 2000, is in need of revision within the context of current market forces and technology (Table #28).

The selection of a specific control technology will likely be made on a case-by-case basis in part due to the unique nature of each semiconductor manufacturing facility. In certain circumstances, gas substitutes may be feasible. Control technologies may provide emission reduction for a wide spectrum of operations; however, there is a concern that some systems may be constrained by new emission control technology based on design and output parameters.

8.0 The Uses and Substitutes of Sulfur Hexafluoride

Sulfur hexafluoride is an inorganic compound with the formula SF₆. It is a colorless, odorless, non-toxic and non-flammable gas (under standard conditions). According to the Intergovernmental Panel on Climate Change, SF₆ is the most potent greenhouse gas that it has evaluated, with a global warming potential of 22,200 times that of CO₂ when compared over a 100 year period.¹³⁵ SF₆ is very stable. Its atmospheric lifetime is 3,200 years. It is generally transported as a liquefied compressed gas. It has a density of 6.13 g/L at sea level conditions.

Of the approximately 8,000 tons of SF₆ produced per year, most of the product is directed to the following worldwide applications based on work by Olivier and Bakker (1999).¹³⁶

- Production of electrical equipment (Gas Insulated Switchgears (GIS), circuit breakers, gas insulated high-voltage lines and mini-stations),
- Utilities (use of electrical equipment - refilling, leakages compensation, accidents etc; use in
- Accelerators for scientific and/or military purposes),
- Magnesium production (primary production and die casting), with application as cover gas in foundries to prevent oxidation,
- Adiabatic properties applications, notably in tennis balls, shoe soles and in truck tires,
- Electronic industry - semiconductor manufacturing (plasma etching and as an etchant before chemical vapor deposition),
- Other applications: soundproof windows, degassing of aluminum specialties, gas tracers, application in medical purposes etc.

According to the EPA, the electric power industry uses roughly 80% of all SF₆ produced worldwide.¹³⁷ SF₆ is used as a dielectric medium in the electrical transmission and distribution industry for high-voltage (35 kV and above) circuit breakers, switchgear, and other electrical equipment. It is often used to replace oil filled circuit breakers (OCBs) that can contain polychlorinated biphenyl's (PCBs). SF₆ gas under pressure is also used as an insulator in gas insulated switchgear (GIS) as it has a much higher dielectric strength than air or dry nitrogen. As a result, this property makes it possible to significantly reduce the size of electrical gear and also makes GIS more suitable for other uses such as indoor placement. The alternative is air-insulated electrical gear that requires considerably more space. Gas-insulated electrical gear is also more resistant to the effects of pollution and climate, as well as being more reliable in long-term operation because of its controlled operating environment. Vacuum circuit breakers (VCBs) are displacing SF₆ breakers in industry as they are safer and require less maintenance.

This section addresses the two largest consumers of SF₆ in the state: electrical utilities and magnesium casting. The semiconductor industry also consumes SF₆; however, this industry sector employs a number of high-GWP gases within the production process. The SF₆ usage by the semiconductor industry is discussed in section 7.0 of this Report. There are approximately 200 entities involved in either generation or distribution of electricity operating in the state of Minnesota. There are approximately 50 magnesium casters in the state operating at various levels of production. The electrical utility analysis is included in section 8.1. Magnesium casting is addressed in section 8.2. All other uses of SF₆ are minimal and will not be included in this analysis.

8.1 Electrical Utility Sector Overview

The Minnesota Department of Commerce characterizes the state's electrical utilities into three categories: investor-owned utilities; cooperative utilities; and municipal utilities. According to information found in the 2005 Minnesota Utility Data Book, there are five investor-owned electric utilities; five generation and transmission cooperatives; 47 distribution cooperatives and 126 municipal cooperatives.¹³⁸ The national total SF₆ emissions from the electrical utilities sector (as a no-action baseline) was estimated to be 15.0 MtCO₂eq in 2000, 17.6 MtCO₂eq in 2010 and 18.9 MtCO₂eq in 2020.¹³⁹ A similar analysis was conducted using a technology adoption baseline analysis with results that predicted 15.0 MtCO₂eq in 2000, 12.8 MtCO₂eq in 2010 and 11.8 MtCO₂eq in 2020.¹⁴⁰

SF₆ is often used as an insulating gas in circuit breakers. A circuit breaker is an electrical switch that is designed to protect an electrical circuit from potential damage caused in situations where the system is overloaded or short circuited. The shut-off mechanism of a circuit breaker operates automatically. A circuit breaker is different than a fuse. Fuses may only be used once and then thrown away, whereas a circuit breaker can be reset either manually or automatically. Circuit breakers are made for a variety of uses that reflect the size and charge of a particular electrical circuit. High voltage circuits use a similar type of circuit breaker device known as switchgear.

The following information on switchgears was extracted from the *Switchgear and Control Handbook*, an industry standard used as a training tool for the operation and maintenance of high voltage systems.¹⁴¹ The term switchgear, refers to the combination of electrical disconnects, fuses and/or circuit breakers that are used to isolate electrical equipment. They are used both to de-energize equipment and to allow for maintenance.

The location of switchgears vary, and are typically located anywhere that isolation and protection may be required. Typical switchgear locations include generators, motors, transformers and substations. A piece of switchgear may be a simple open air isolator switch or it may be insulated by some other substance. An effective although more costly form of switchgear is known as the "gas insulated switchgear" (GIS). The GIS system contains pressurized SF₆ to insulate the conductors and contacts. Other common types of systems include oil or vacuum insulated switchgear.

The design of switchgear allows the device to interrupt fault currents of many hundreds or thousands of amps. The quenching of the arc when the contacts open requires careful design, and falls into four types:

- Oil circuit breakers rely upon vaporization of some of the oil to blast a jet of oil through the arc.
- Gas (SF₆) circuit breakers sometimes stretch the arc using a magnetic field, and then rely upon the dielectric strength of the SF₆ to quench the stretched arc.
- Vacuum circuit breakers have minimal arcing (as there is nothing to ionize other than the contact material), so the arc quenches when it is stretched a very small amount (<2-3 mm). Vacuum circuit breakers are frequently used in modern medium-voltage switchgear to 35,000 volts.
- Air circuit breakers may use compressed air to blow out the arc, or alternatively, the contacts are rapidly swung into a small sealed chamber, the escaping of the displaced air thus blowing out the arc.

8.1.1 Alternatives

The alternatives available for the energy sector use of SF₆ are somewhat limited. There are ranges of circuit breaker designed that do not use SF₆; however, each of these approaches has limitations. Nearly all circuit breaker systems used by the electrical utilities in Minnesota employ some form of an SF₆ breaker system.

8.1.2 Case Study

The MPCA contacted Great River Energy (GRE) to gain additional information on the use of SF₆ within the electrical utility sector. GRE is a not-for-profit generation and transmission cooperative serving approximately 600,000 customers through 28 member cooperatives. The GRE service area covers approximately 2/3 of the state of Minnesota and a portion of northwestern Wisconsin. GRE has generation facilities throughout Minnesota and two coal-fired facilities in North Dakota. GRE has SF₆ equipment in Minnesota and North Dakota, with all SF₆ gas and gas-containing equipment purchases originating in Minnesota. The SF₆ is used primarily in gas-insulated circuit breakers.

The amount of SF₆ gas varies by equipment style and model. System-wide, GRE's equipment contains ~ 45,000 lbs. of SF₆. All SF₆ gas-containing devices have temperature compensated pressure alarms that are continuously monitored by the GRE System Operations Control Center. In addition, all of GRE's SF₆ gas-containing equipment is located in secured facilities which are routinely monitored and inspected on a frequent basis. Finally, GRE uses a variety of inspection and diagnostic leak technologies to identify and resolve specific equipment leak issues. In-house staff are trained and experienced in the handling of SF₆ gas, and the operations and maintenance of SF₆ gas-insulated equipment.

As part of GRE's membership in EPA's Voluntary SF₆ Emission Reduction Partnership for Electric Power Systems, the company tracks SF₆ emissions. In 2007, GRE emitted 1,523 lbs of SF₆ gas. In 2008 (through October 31, 2008) GRE lost only 367 lbs of SF₆ gas.

According to the GRE experience, some systems are subject to greater SF₆ losses than others. Based on GRE records, earlier vintage, dual-pressure, dead-tank SF₆ circuit breaker designs are significantly more prone to SF₆ gas leaks. This is primarily due to a substantially greater total gasket surface area. These types of circuit breakers have consistently been the major contributors of SF₆ gas leaks, and have received a disproportionate amount of investment in an attempt to mitigate the leak sources.

GRE pursues equipment replacements where new SF₆ circuit breaker design technologies are available that meet the specific transmission system design requirements. This is not always an available option. Additionally, non-SF₆ equipment technology options are not available for the vast majority of transmission-level voltage design applications.

Since 2001, GRE has invested \$1.3 million to replace earlier vintage, dual-pressure, dead-tank SF₆ circuit breakers. In cases where equipment replacement was not an option due to design limitations and equipment performance requirements, GRE invested significantly in the overhaul and rebuilding of the existing devices. To this point, since 2001, GRE has invested \$2.6 million system-wide for maintaining its fleet of existing circuit breakers, of which, \$708,000 was spent on the older, dual-pressure, dead tank breakers. This is significant when you consider that these units account for only slightly over four percent of GRE's circuit breaker fleet. GRE routinely

spends in the neighborhood of \$200,000 annually, performing routine facility inspections, which include specific inspection checks on SF₆ circuit breakers.

Typical strategies employed during these overhaul and rebuilding efforts include upgrading of system components and re-gasketing. Typical failure paths for SF₆ circuit breakers include:

- Factory design defects - porous castings, faulty gas manifold tubing, defective pressure relief devices, internal electrical faults
- Weather – drastic changes in ambient temperatures and failure of gasket systems
- Age – corrosion of gasket surfaces due to environmental factors, faulty SF₆ gas re-pressurization system components

8.1.3 Cost Analysis

The information presented in Table #29 and Table #30 present the EPA 2008 analysis on the emission reduction and costs projected to 2020. The analysis included both a no-action and technology adoption baseline.

Table #29 – National Emission Reduction and Costs in 2020 – No-Action baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
	Recycling	-\$0.61				
Decommissioning	\$1.47	\$1.47	1.04	1.6	31.69	48.2
Awareness/training	\$2.04	\$2.04	0.32	0.5	32.01	48.7
Leak detection	-\$0.56	\$2.68	4.38	6.7	36.39	55.3
Refurbishment	\$5.01	\$5.01	0.93	1.4	37.32	56.7
Evacuation	\$27.28	\$27.28	0.01	0.0	37.33	56.8
Repair and replacement	\$45.51	\$45.51	0.04	0.1	37.36	56.8

Table #30 – National Emission Reduction and Costs in 2020 – Technology Adoption Baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
	Recycling	-\$0.61				
Decommissioning	\$1.47	\$1.47	0.00	0.0	24.61	42.8
Awareness/training	\$2.04	\$2.04	0.00	0.0	24.61	42.8
Leak detection	-\$0.56	\$2.68	3.17	5.5	27.78	48.3
Refurbishment	\$5.01	\$5.01	1.10	1.9	28.88	50.2
Evacuation	\$27.28	\$27.28	0.00	0.0	28.88	50.2
Repair and replacement	\$45.51	\$45.51	0.00	0.0	28.88	50.2

The most effective option for this sector appears to be recycling, with leak detection a distant second choice and decommissioning/refurbishing a third option, depending on the nature of the MAG curve (no-action v. technology adoption baseline).

8.2 Magnesium Casting Sector Overview

Molten magnesium will oxidize (burn), sometimes explosively, if it comes in contact with ambient air. Therefore, the industry has developed the use of cover materials as melt protection to prevent burning the surface of the molten metal. Historically, sulfur dioxide and salt fluxes were used to protect the metal's surface. However, those materials had disadvantages that included reduced metal quality and equipment corrosion. As a result, the industry has used SF₆ since the 1970s because it is nontoxic, noncorrosive and nonflammable. The EPA calculated a national no-action and technology-adoption baseline for the emissions for SF₆ from the magnesium casting industry. The no-action baseline predicted that SF₆ emissions would have been 3.2 MtCO₂eq, in 2000, 4.6 MtCO₂eq in 2010 and 6.4 MtCO₂eq in 2020.¹⁴²

The major source in the magnesium industry of SF₆ consumption is primary smelting, which uses between 50 and 75 percent of the industry's total. There are no magnesium smelters in Minnesota. Magnesium casting – both die casting and gravity casting – along with magnesium recycling (also called secondary smelting) comprises the remainder of SF₆ use in this sector. Minnesota has approximately 50 magnesium casting facilities.

Production of magnesium castings has been a growth sector in recent years. This growth results from the demand from the automotive, aerospace and portable electronics industries for light weight or complex parts. Die casting, which forms parts by injecting molten magnesium into a metal mold, is the second-largest end use of magnesium. The SF₆ concentration in the cover gas is typically in the range of 0.2-0.3% by volume in air or CO₂. Gravity casting, in contrast, is a manual process where molten metal is poured into a sand mold. Gravity casting furnaces are often more open to the air and thus more SF₆ is consumed – a typical range is 1.7-2.0 percent by volume in CO₂.¹⁴³

While SF₆ has been used as a degassing agent for molten aluminum, this practice has been largely discontinued in favor of argon or chlorine gases. No SF₆ is needed as a cover gas for aluminum alloys combined with magnesium because magnesium ingots are immersed in the melted aluminum.

The EU has banned the use of SF₆ in magnesium production as of 2008 if the quantity used is over 850 kg/yr (EC Regulation No. 842/2006, May 17, 2006). The US EPA and industry sources have been working in partnership to voluntarily eliminate the use of SF₆ by 2010.

8.2.1 Alternatives

8.2.1.1 Control Technology & Practice

Leakage of SF₆ can be reduced with good housekeeping practices such as daily leak detection and maintenance of key components such as flow meters, lines, and crucible lids, as well as monthly flow meter calibration. In addition, centralized cover gas mixers, use of external manifolds, use of high gas velocity and minimizing moisture in the system are also helpful. Air Liquide America developed a capture/recycle system for SF₆ that showed promising results in a pilot test. However, replacing SF₆ with another material is the preferred option.

8.2.1.2 Substitutes and Costs

Alternatives to SF₆ are available that have lower GWPs and do not deplete the ozone layer. These alternatives may offer other advantages that include reduced material cost, reduced metal loss, less smoke and fumes, and nonflammability. Conversion to one of the substitute materials

must include consideration of the best carrier gas for the new materials, concentration, flow rate, distribution and operating conditions.

The table below summarizes the characteristics of several commercially available and potentially available substitute gases. Novec™ 612 is a patented liquid-to-gas system using a fluorinated ketone (FK) in a carrier gas such as CO₂ or nitrogen and dry air. AM Cover™ is contains an active gas (HFC-134a) and a carrier gas such as CO₂ or nitrogen. A dilute SO₂ system uses a mixture of approximately 1.5% SO₂ with CO₂, nitrogen or dry air as a carrier gas.¹⁴⁴

While the substitute materials offer GWP advantages over SF₆, they are not without potential concerns with byproducts, SO₂, HF, and BF₃ are toxic at low levels and may corrode equipment. PFIB and SO₂F₂ are toxic. PFCs are also high-GWP gases. Therefore, care must be taken to use good operating practices to minimize production of and harm from these potential byproducts.

Table #31 - Summary of Substitutes for Magnesium Melt Protection

Compound	Atmospheric Lifetime (yrs)	GWP (100 years)	Potential reduction vs. SF ₆	Potential Byproducts of Concern	Upgrade needed from SF ₆ system
Commercially Available					
FK (Novec™ 612)	0.014	~1	95-99%	HF, PFIB, PFCs	Moderate
HFC-134a (AM Cover™)	14.6	1,300	95-99%	HF, PFCs	Minimal
Dilute SO ₂	Several days	0	NA	SO ₂	Significant
Under Development					
BF ₃	?	Not measured	?	BF ₃	Moderate
SO ₂ F ₂	?	~1	?	SO ₂ , HF	Significant

Source: US EPA. Alternatives to SF₆ for Magnesium Melt Protection. EPA-430-R-06-007. 2006

The 2001 EPA analysis estimated the cost of replacing SF₆ with SO₂ at \$0.25/TCE. This cost included retrofitting expenses, purchasing SO₂-compatible equipment and employee training. Other cost savings from material substitution may include reduced material cost, reduced metal loss.

The 2008 EPA report included an evaluation of recycling and decommissioning option for the magnesium casting sector. Each evaluation was conducted for a no-action and technology adoption baseline (Table #32 and Table #33 respectively) to the year 2020. Under each scenario, recycling was the most effective practice.

Table #32 – National Emission Reduction and Costs in 2020 – No-Action baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
Recycling	\$0.53	\$0.79	10.90	60.3%	10.90	60.3%
Decommissioning	\$1.21	\$1.48	6.95	38.5%	17.85	98.8%

The amount recovered through recycling under the technology adoption baseline is less than the amount recovered under the no-action baseline. The difference reflects the existing use of controls via voluntary industry initiatives.

Table #33 – National Emission Reduction and Costs in 2020 – Technology-Adoption Baseline (EPA, 2008).

Reduction Option	Cost (2000\$/tCO ₂ eq) DR=10%, TR=40%		Emissions Reduction Option (MtCO ₂ eq)	Reduction from 2020 baseline (%)	Running sum of reductions (MtCO ₂ eq)	Cumulative reduction from 2020 baseline (MtCO ₂ eq)
	Low	High				
Recycling	\$0.53	\$0.79	4.19	86.6%	4.19	86.6%
Decommissioning	\$1.21	\$1.48	0.44	9.2%	4.63	95.8%

9.0 Consumer Products

As noted in section 2.0, Other State, National and International high-GWP approaches, California in June 2008 adopted a Discrete Early Action measure to reduce high-GWP gases in consumer products.^{xiii} Consumer products, in this case, include floor cleaner, aerosol air freshener, oven cleaner, paint and paint thinners, pressurized gas dusters, and various other adhesives and cleaners. In general, consumer products mainly contain GHGs as propellants in aerosols. However, some consumer solvents also contain high-GWP gases.

California already has regulations to achieve the maximum feasible reduction in emissions of volatile organic compounds (VOCs) from consumer products. The basis of the regulation, originally promulgated in 1988, was to reduce emissions that contribute to ground-level ozone; emission reductions from consumer products have been included in California's State Implementation Plan (SIP) for meeting national ozone standards.

Three total consumer product regulations have been adopted to date, affecting 115 categories of products and setting 150 VOC limits. There are also two voluntary regulations that have been adopted. All of these regulations are in Title 17, California Code of Regulation, Sections 94500 to 94575. Some high-GWP potential gases are also VOCs, and have therefore been at least somewhat regulated under this program. However, many of high-GWP gases have been exempt because they are minimally photochemically reactive, and have therefore seen some increasing use as attempts are made to reduce the VOC content of consumer products. These include HFCs, HCFCs, HFEs, CO₂, and N₂O. The focus of California's proposed new regulations is to reduce the use of HFC-134a as a propellant in consumer products.

In developing existing and potential new regulations, CARB established the Consumer Products Regulation Workgroup in 2004. Any member of the public can participate in the workgroup; the workgroup has been extensively involved in the proposed amendments to the consumer products regulation. Workgroup members have included product manufacturers, producers, marketers, trade associations, environmental groups, local air districts and others.

The implementation of the discrete early action measure to reduce emissions of GHGs from consumer products is estimated to result in annual GHG emission reductions of 0.20 million MtCO₂-eq. The objective of the measure is to reduce the use of high-GWP potential gases in consumer products when alternatives are available; reformulation of products to meet the limits is expected.

At this time, CARB is proposing amendments to the regulations in order to set the first specific GWP limit for consumer products (as well as add or update many VOC limits on other consumer products.) The regulation proposes a GWP limit on pressurized gas dusters (excluding those where flammability concerns lead to a lack of suitable alternatives.) These are a key category because they are composed of 99 – 100% propellant. Total 2008 GHG emissions from pressurized gas dusters in California are estimated to be 0.37 million MtCO₂-eq.

^{xiii} This section relies upon work conducted by the California Air Resource Board (CARB) during their rulemaking activities related to global warming potential and consumer products. This work can be found in the CARB document entitled "Initial Statement of Reasons for Proposed Amendments to the California Consumer Products Regulation." <http://www.arb.ca.gov/regact/2008/cp2008/cpisor08.pdf> (accessed on December 4, 2008), and the CARB document "Rulemaking to Consider Adoption of Proposed Amendments to the California Consumer Products Regulation." <http://www.arb.ca.gov/regact/2008/cp2008/cp2008.htm> (accessed on December 4, 2008).

The limits being proposed are that pressurized gas dusters be limited to using compounds with GWP of 150 or less. Restrictions on VOC content and use of chemicals that are considered air toxics are also included, to avoid adverse environmental impacts from switching away from high-GWP gases. It is expected that pressurized gas dusters will be reformulated to replace HFC-134a with HFC-152a, which has a GWP of 140; 18 of 90 products already meet the limits proposed.

The regulation also proposes a one-year “sell-through” period, in which stocks of products can continue to be sold, after the effective date of the regulation (December 31, 2010). In terms of cost, CARB has estimated that the requirement to reduce GHG emissions from pressurized gas dusters will cost \$450,000 over 10 years (\$45,000/year.) The cost-effectiveness of this measure is about \$0.22 per MtCO₂-eq reduced. HFC-152a is cheaper per pound than HFC-134a. As noted previously, the measure is expected to result in annual GHG emission reductions of 0.20 million MtCO₂-eq.

CARB did consider a technology-forcing standard that would not allow use of any compound with a GWP greater than 10 after December 31, 2015. This was based on the fact that there is some use of CO₂ in gas dusters and information about new refrigerants under development. However, CARB determined that CO₂ dusters are not commercially competitive and not enough is known about the VOC status of new low GWP refrigerants and how they might work as propellants in consumer products. CARB will continue to research this area.

Although at this time, CARB is only looking at regulations for pressurized gas dusters, and these appear to result in a large portion of the total reductions from consumer products estimated in the AB32 scoping plan, it is anticipated that CARB will continue to evaluate additional GWP limits for consumer products in California.

10.0 Recommendations

This Report provides approximations of the costs of control for high-GWP gases in Minnesota. The MPCA reviewed the analysis in light of the MCCAG recommendations on climate change control options. This section is specifically focused on MCCAG recommendation RCI-5, specific to a Program to Reduce Emissions of Non-Fuel, High-Global-Warming-Potential GHGs. The recommendation reads as follows:¹⁴⁵

High-global-warming-potential (high-GWP) GHGs are classes of chemicals that have a number of commercial and industrial uses. They include the chemical species hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). [footnote omitted] This policy recommends that the Minnesota Pollution Control Agency (MPCA) undertake a rulemaking process to identify uses and emission sources of HIGH-GWP GHGs and to eliminate the use or escape of such gases where that can be done at a reasonable cost.

The MCCAG offered a three-pronged policy design to address the high-GWP gases:¹⁴⁶

- Elimination of emissions of high-GWP GHGs at reasonable cost;
- Promotion and funding for process optimization; and,
- Use of lower-impact alternatives for coolants, refrigerants, aerosols, solvents, and insulation.

To implement the policy directions identified above, the MCCAG identified the following mechanisms:¹⁴⁷

- MPCA rulemaking process.
- Legislative action to provide tax incentives and funding for technical support and assistance.
- Technical support through the Minnesota Technical Assistance Program (MnTAP) or similar entities.

Each of the MCCAG policy directions, along with the identified implementation strategies, are discussed in this section with information generated from the technical and cost effectiveness analysis provided in this Report. The MPCA offers the following two specific recommendations based on the sector review and the MCCAG Climate Change Action Plan:

Recommendation #1

The MPCA recommends that a rule scoping process be conducted to develop a rule to reduce high-GWP emissions through reasonable cost efforts. As noted in the sector evaluations, many of the sectors appear to be able to reduce emissions within a \$15 a ton carbon dioxide equivalent control cost. A rule scoping process would provide for greater resolution of the sector-specific operations that could lead to more cost-effective regulation and could commence in 2009 with completion in 2011. This process would include consideration of appropriate product bans.

Within the rule-scoping process, the MPCA would also be able to determine the role of a voluntary emissions reduction program in an overall statewide strategy of high-GWP emission reduction. Several voluntary industry and EPA-sponsored programs exist; however, most Minnesota companies are not currently participating. The rule scoping process would be useful in determining the opportunities for volunteer emission reduction program membership based on potential emission control technology and substitutes.

Recommendation #2

The MPCA recommends that the current high-GWP reporting scheme be converted to an emission-based program, along with an increase in the mandatory reporting threshold. The rationale for this approach is based on the nature of high-GWP gas usage and purchase behavior. The purchase of high-GWP gases is not a robust surrogate for determination of annual emissions for comparison to the targets in the Next Generation Energy Act. The use of high-GWP gas purchases as a means to evaluate emissions is imprecise, in part because of the lack of alignment between purchase and gas usage within the state. As noted above, the purchase of high-GWP gases must be made within the state and above the specific reporting threshold in order to be subject to reporting. Many large high-GWP gas consumers purchase their high-GWP commodities outside the state, thereby eliminating the need to report.

The emission reporting threshold should be increased to a value consistent with programs in other states and countries. Thresholds in other states range between 2,500 and 100,000 tons of carbon dioxide equivalent, with most states pursuing thresholds in the range of 10,000 tons. The rationale for this value is based on the administrative burden placed on smaller generators of high-GWP emissions with respect to cost and the need to focus regulatory resources on facilities that are high-volume emitters of high-GWP gases. Minnesota is one of the few states that specifies a high-GWP reporting threshold rather than an aggregate of all climate change gases (i.e., combination of CO₂ and non-CO₂ gases). A long-term goal of the Next Generation Energy Act is to reduce GHG emissions consistent with specific statutory targets and deadlines. Emission reporting is the manner in which statewide performance is evaluated with these expectations. Shifting the focus from high-GWP purchases to a facility-specific emission reporting requirement would further the implementation of the Next generation Energy Act.

The development of an emission reporting scheme would be best served through the rule scoping process. A rule scoping process would allow the MPCA to better identify participants, basic data elements (including reporting thresholds), reporting frequency, *de minimis* values and the scope of reporting (e.g., sectors, direct and indirect emissions). The reporting process should also harmonize the high-GWP activities with other climate change activities proposed by MCCAG including greenhouse gas reporting. The remainder of this section is a summary of the data analysis that aligns to the recommendations provided above.

10.1 Elimination of Emissions of HIGH-GWP GHGs at Reasonable Cost.

The first policy direction provided by the MCCAG was the elimination of high-GWP emissions at a reasonable cost. The MCCAG noted that “For purposes solely of calculation of the costs and effects of this recommendation, a reasonable cost is determined to be \$15 per ton CO₂ equivalent.”¹⁴⁸ The MPCA notes that many of the sectors reviewed may be able to reduce emissions within the \$15 cost criteria. The information provided in Table #34 is a review of the predicted national baseline data by sector, the potential reductions that are achievable using the \$15 breakeven price, and the percent reduction if control technology is adopted. This information is presented for the years 2010 and 2020.

Table #34 - National Emission Reduction and Cost Analysis using a \$15/tCO₂e Control cost (EPA, 2008).

Sector	2010 Baseline (MtCO ₂ e)d	2010 a Reduction (\$15/tCO ₂ e)d	2010 b Reduction (%)	2020 Baseline (MtCO ₂ e)	2020 a Reduction (\$15/tCO ₂ e)	2020 b Reduction (%)	Options/Comments
Refrigeration (auto and stationary)	148	11.5	7.8	264	78	29.5	Least cost are leak repair for large system, recovery for small system and enhanced HFC-134a system for mobile air conditioning.
Solvent	1.7	0.43	25.3	2	1.05	52.5	Substitution and improved system design
Foams	5.7	0.2	3.5	11.3	1.17	10.4	Substitution
Aerosol - medical	2.7	0	0	5.5	0	0	No effective substitutes
Aerosol - other	12.1	4.67	38.6	14.8	8.43	57.0	Assumes no effective voluntary program – “no action” baseline
Fire protection	1.6	0	0.0	1.9	0	0.0	Long life of installed system - replacements being developed
Semiconductors	28.2	20.0	70.9	46.1	32.7	70.9	Assumes “no action” baseline
Magnesium Casting	4.6	4.5	97.8	6.4	6.26	97.8	There is an IMA goal to phase out by 2011 but participation in MN is not known - assumed "no action" baseline
Electrical Utilities SF ₆	17.6	10.05	57.1	18.9	10.78	57.0	Assumes “no action” baseline
Total	222.2	51.35	23.1 c	370.9	138.39	37.3 c	

a This column represents the amount removed by sector at a cost of \$15 per ton of carbon dioxide equivalent.

b This column represents the percentage of pollutants removed, by sector, from the overall baseline for 2010 and 2020.

c The value in the shaded area represents the overall percentage of pollutants removed from all sectors in comparison to the baseline for 2010 and 2020.

d Million ton of carbon dioxide equivalent (MtCO₂e) – Dollars per ton of carbon dioxide equivalent (\$/tCO₂e).

Note that the emissions of HFCs and PFCs are expected to increase past 2010 in part due to the replacement of CFC chemicals under the Montreal Protocol. Based on the information in Table #34, the magnesium casting sector would be able to achieve the greatest percentage of reductions using the \$15 control cost criteria. The electrical utilities sector offers the second greatest reduction from the emission baseline, with the semiconductor manufacturing and refrigeration sectors presenting a similar reduction capacity.

Each of the sectors reviewed presents different emission control challenges. Emissions from the refrigeration sector (Section 4.0) are typically a product of leaks, either through operation of the

units or through accidents during servicing and recycling. While a number of suitable (i.e., non-high-GWP gases) refrigerants exist, many of these products are not used commercially at this time. Substitutes and leak detection/repair are two technical recommendations that may be successful at a reasonable cost.

The foam and fire protection sectors appear to have the smallest reduction potential from the baseline condition in both 2010 and 2020. The commercial foam sector uses some foam-blowing agents that contain HFCs (Section 5.0). The standard approaches to address these issues are the use of substitute blowing agents, production processes and to some extent, process control technologies that capture emissions during the manufacturing process. The foam manufacturing industry is highly diverse. Each control strategy would be unique to a company process, thereby complicating the cost analysis. A rule scoping process would facilitate the development of a control strategy for this sector.

The fire protection sector, discussed in Section 6.0, has a unique emission characteristic in that the discharge of a total flooding suppression system during a fire event is nearly the only means by which HFCs would be emitted. The only effective approaches in this situation is the use of a substitute that does not present a high global warming potential and policy direction on reuse and recovery activities of existing products. A rule scoping process would provide useful information on the operational aspects of these systems.

Three of these sectors are able to participate in industry and EPA-sponsored voluntary emissions reduction programs to address the use of high-GWP gases. The semiconductor manufacturing industry (Section 7.0), electrical generation and transmission sector (Section 8.1), and the magnesium casting sector (8.2). The semiconductor manufacturing sector presents a situation in which control technology exceeds the reasonable cost of \$15 a ton. While some substitutes are available, they are not widely used. Currently, Minnesota has six operating semiconductor manufacturing facilities of various sizes. Based on information provided through the industry, there are currently no efforts underway to implement high-GWP emission control technology in Minnesota. The major issue is cost. None of these facilities are currently participating in the industry and EPA-sponsored programs.

The electrical generating and transmission sector uses sulfur hexafluoride as a quenching agent in circuits and switchgears. According to industry contacts, the use of this gas will continue as there have not been any suitable replacements. For this sector, leak detection, refurbishment and decommissioning are the only options available – oftentimes exceeding the \$15 per ton breakeven price. Only one of the nearly 200 electrical generating and transmission sector operations participates in the industry and EPA-sponsored voluntary emissions program.

The magnesium casting sector in Minnesota is highly variable with respect to process; however, all systems use a cover gas. Sulfur hexafluoride has been the cover gas of choice for several decades. Several substitutes and closed-chamber technologies exist. The substitute that appears to have market affinity is sulfur dioxide. Sulfur dioxide is cheaper and requires less gas to achieve the same results. In addition, it is not an high-GWP. Technology to use substitutes is available; however, there are issues of transition cost that affect the control cost of \$15 per ton. Only two magnesium casting facilities are currently participating in the industry and EPA-sponsored programs.

The MCCAG recommendation specifies that the MPCA should pursue rulemaking to address emissions of high-GWP gases. The language of the recommendation provided for a structured rulemaking process that operates through an initial scoping process to construct regulatory categories under which to apply the rule. The regulatory categories are constructed using the reasonable cost definition of \$15 a ton of carbon dioxide equivalent and the existence of a voluntary emission reduction program. Under this approach, it is assumed that a sector by sector approach would include a combination of facilities that would be exempt from regulation, those that would be regulated and those that would benefit from incentives and training.

An example of a similar regulatory approach is the current California Stationary High Global Warming Refrigerant Management Program.^{xiv} The general structure of the program operates through three specific categories: leak repair; sale and disposal; and New R/AC systems (see Figure #3):

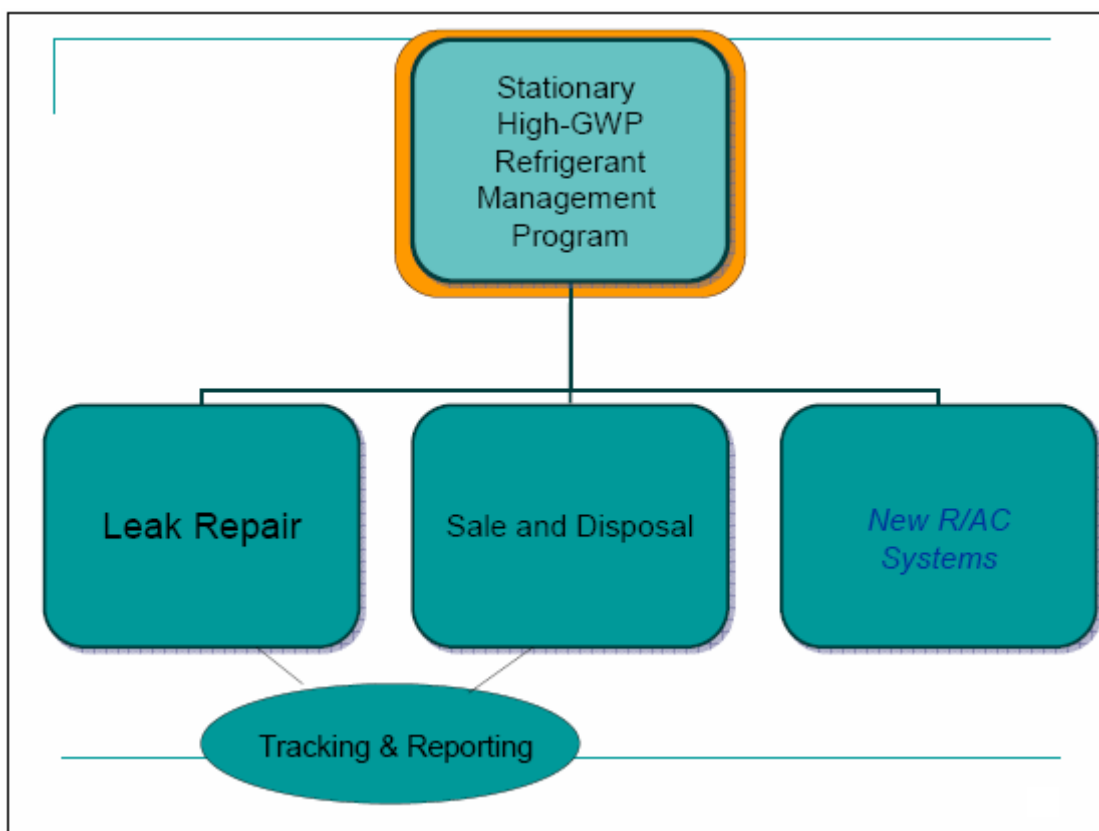


Figure #5 – Overview of the California Stationary High Global Warming Potential Management Program

The state of Minnesota currently has a statute and rule that operates in a similar fashion to address the release of CFCs from mobile source and stationary air conditioning systems. Elements of this approach could be applied to other sectors and include elements of a program to induce participation in voluntary emission reduction programs, where available.

^{xiv} As part of the California Global Warming Solutions Act of 2006 (AB 32) the ARB has approved an early action measure to reduce high-global warming potential (GWP) greenhouse gas (GHG) emissions through establishing requirements for enhanced monitoring, enforcement, reporting, and recovery of high-GWP refrigerants. <http://www.arb.ca.gov/cc/reftrack/reftrack.htm> (accessed on January 20, 2009)

A rulemaking scoping process would provide the MPCA with a better range of opportunities for emission reduction and effective administration. This activity would generate a better understanding of the regulatory status for each sector and the most effective means by which to phase in a new rule. The MCCAG recommended that the MPCA use a phased approach to rule administration that would meet the following criteria:¹⁴⁹

- Require the elimination of HIGH-GWP GHGs, on a phased basis, where this can be done at no cost;
- Require the elimination or reduction of such gases by the use of prudent managerial practices, process changes, and improved technology or by substitution of other substances, or other means, where the cost of CO₂e reduction can be accomplished at a reasonable cost.
- Establish the reasonable cost per ton of CO₂e reduction, taking into account the availability of alternatives.

The expected outcome of this scoping process would be a combination of mandatory and voluntary activities that result in a reduction of high-GWP gases from the sectors identified in this Report. The activities range from no-cost reductions to an alternatives assessment based on cost effectiveness. It appears that most of the sectors reviewed have potential for reduction of high-GWP gases. A more careful review of each sector, in consultation with sector representatives, would offer greater opportunity for more effective rule development.

10.2 Promotion and Funding for Process Optimization.

The second policy direction provided by MCCAG was the promotion and funding for process optimization. The policy statement as drafted provides for the following:

If HIGH-GWP GHGs can be eliminated at a reasonable cost, MPCA should mandate this through the rulemaking process (if it has not been done voluntarily through EPA programs or otherwise). In other cases, *the state should provide funding and incentives for the reduction and phaseout of HGP GHGs, through tax incentives and funding for programs that offer education and technical assistance.* [Italics added]

This policy is directed at situations where the abatement costs are higher than the reasonable \$15 control cost, and likely recognizes the absence of a voluntary emissions reduction program.

The industry and EPA-sponsored programs are voluntary in nature and offer opportunities for educational/technical assistance that is intended to lead to lower GHG emissions. These programs are directed at semiconductor manufacturing, electrical generation and transmission, and magnesium casting. The state could develop a specific inducement program that would facilitate industry entry into the program; or, it could become part of a broader rule-based application. The MPCA recommends that a rule-scoping process would greatly assist in the determining the role of a voluntary emissions reduction program into an overall statewide strategy of GHG emission reduction.

10.3 Inventory of high-GWP gases in Minnesota

The MPCA conducted an initial high-GWP reporting effort of purchasers and manufacturers of high-GWP gases. A review of other state program efforts was useful in evaluating the existing

Minnesota approach. The current reporting structure in Minnesota is focused specifically on purchase (or manufacture) of high-GWP gases. For the manufacture of high-GWP gases, there is no specific reporting threshold. For purchasers, any purchase that exceeds 500 metric tons of carbon dioxide equivalent is subject to reporting.

The Minnesota approach offers some useful information on emissions for certain sectors; however, it is an insufficient surrogate for emissions when a facility participates in purchase and bank behavior, whereby a purchase in excess of need is made of a particular high-GWP gas product. This is not to make claim that reporting purchases of high-GWP gases is ineffective – rather – reporting may be more effective if it is offered through emissions data rather than specific purchase date. Emission data would allow for the consumption of high-GWP gases in various products and also identify situations where banking of gases occurs. In addition, emissions reporting pursuant to a rule would allow the MPCA to develop sector-based approaches to address such issues as participant reporting categories, *di minimis* values, specific emission calculation methodologies and related administrative activities.

Another feature that affects the reporting of purchases is the very low high-GWP reporting threshold. Many small entities are now expected to report under the current 500 metric ton (carbon dioxide equivalent) reporting threshold. The amounts of high-GWP gases that exceed this threshold are typically quite low, with some gas types below 100 pounds. The burden for small businesses to manage the accounting and reporting of these purchases may be substantial. There is an additional administrative burden placed on state resources to manage and account for all potential high-GWP purchases. Many of the purchasers may change their reporting status year to year depending on the nature of their business, market price of the high-GWP gases, etc. Other states have specifically addressed carbon dioxide or a combination of carbon dioxide and non-carbon dioxide gases with high-GWPs through reporting thresholds that are much higher than the Minnesota law. The state of Oregon noted:¹⁵⁰

California and Wisconsin established a minimum emissions reporting threshold of 25,000 metric tons and 100,000 tons of CO₂ equivalents, respectively. California's minimum emissions reporting threshold of 25,000 metric tons is only relevant for fuel combustion activities. Wisconsin's minimum emissions reporting threshold is for all sectors and categories of greenhouse gas emissions activities.

The state of New Jersey currently uses a 2,500 ton threshold, while Massachusetts uses 5,000 tons. A number of other states and regional climate registry programs either use or intend to use reporting thresholds as high as or higher than 10,000 metric tons. The higher reporting thresholds are more useful in identifying large high-GWP emitters.

In sum, the MPCA recommends that the current high-GWP reporting requirement be based on emissions rather than purchase of high-GWP gases. The MPCA further suggests that a higher reporting threshold may be appropriate. These recommendations may be best implemented through the rule scoping process to better identify participants, basic data elements (including reporting thresholds), reporting frequency, *di minimis* values and the scope of reporting (e.g., sectors, direct and indirect emissions).

Works Cited

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- ¹ Minnesota Climate Change Advisory Group, 2008. Final Report. A Report to the Minnesota Legislature. Saint Paul, MN. EX-2.
 - ² Emissions of greenhouse gases in the United States 2000 - Energy Plug - Brief Article - Statistical Data Included. Monthly Energy Review, November, 2001.
http://findarticles.com/p/articles/mi_m2744/is_11_2001/ai_80805346 (accessed 27 Oct. 2008).
 - ³ Deeds, D. A. 2008. The natural geochemistry of tetrafluoromethane and sulfur hexafluoride: Studies of ancient Mojave Desert groundwaters, North Pacific seawaters and the summit emissions of Kilauea volcano. Scripps Institution of Oceanography Technical Report.
<http://repositories.cdlib.org/sio/techreport/80> (accessed November 14, 2008).
 - ⁴ Calm, James M. 2002. The next generation of refrigerants – Historical review, considerations, and outlook. *International Journal of Refrigeration*, 31(7): 1123-33.
 - ⁵ Calm, James M. Options and outlook for chiller refrigeration. 2002, *International Journal of Refrigeration*, 25(7): 708.
 - ⁶ Ibid.
 - ⁷ Freon. <http://inventors.about.com/library/inventors/blfreon.htm> (accessed October 17, 2008).
 - ⁸ Lovelock, J.E., Maggs, R.J. and Wade, R.J. 1973. Halogenated hydrocarbons in and over the Atlantic. *Nature*, 241: 194-196.
 - ⁹ Maclaine-Cross, I.L. and Leonardi, E. 1996. Comparative performance of hydrocarbon refrigerants.
<http://www.hychill.com.au/pdf/cpohcr.pdf> (accessed November 18, 2008).
 - ¹⁰ Farman, J. C., B. G. Gardiner, and J. D. Shanklin. 1985. Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. *Nature* 315: 207-10.
 - ¹¹ Intergovernmental Panel on Climate Change. 2001. Climate Change 2001: The Scientific Basis. <http://www.ipcc.ch/ipccreports/tar/wg1/index.htm> (accessed on October 17, 2008).
 - ¹² Tsai, Wen-Tien, Chen, Horng-Ping and Wu-Yuan Hsien. 2002. A review of uses, environmental hazards and recovery/recycle technologies of perfluorocarbons (PFCs) emissions from the semiconductor manufacturing processes. *Journal of Loss Prevention in the Process Industries*, 15(2), 65.
 - ¹³ Huang L, Shen Y, Dong W, Zhang R, Zhang J, Hou H. 2008. A novel method to decompose two potent greenhouse gases: photoreduction of SF₆ and SF₅CF₃ in the presence of propene. *J. Hazard Mater.*, 151(2-3):323.
 - ¹⁴ Ibid.
 - ¹⁵ Intergovernmental Panel on Climate Change. Climate Change 2007: the Fourth Assessment Report (AR4), Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (accessed October 20, 2008).
 - ¹⁶ Inventory of U.S. Greenhouse Gas Emissions and Sinks (2008), EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 (April 2008) USEPA #430-R-08-005.
 - ¹⁷ United States Environmental Protection Agency. Stratospheric Ozone Protection and Climate Change. <http://www.epa.gov/Ozone/climate.html> (accessed October 20, 2008).
 - ¹⁸ United States Environmental Protection Agency. GreenChill Advanced Refrigeration Partnership. <http://www.epa.gov/Ozone/partnerships/greenchill/index.html> (accessed October 20, 2008).
 - ¹⁹ United States Environmental Protection Agency. SF₆ Emission Reduction Partnership for Electric Power Systems. <http://www.epa.gov/highhigh-GWP/electricpower-sf6/index.html> (accessed October 20, 2008).
 - ²⁰ United States Environmental Protection Agency. SF₆ Emission Reduction Partnership for the Magnesium Industry. <http://www.epa.gov/highhigh-GWP/magnesium-sf6/index.html> (accessed October 20, 2008).
 - ²¹ United States Environmental Protection Agency. Voluntary Aluminum Industrial Partnership (VAIP). <http://www.epa.gov/highhigh-GWP/aluminum-pfc/index.html> (accessed October 20, 2008).

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- 22 United States Environmental Protection Agency. PFC Reduction / Climate Partnership for the Semiconductor Industry. <http://www.epa.gov/high-GWP/semiconductor-pfc/index.html> (accessed October 20, 2008).
- 23 California Air Resources Board. AB32 Proposed Scoping Plan. <http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm> (accessed October 20, 2008).
- 24 California Air Resources Board. AB32 Proposed Scoping Plan, p 61. <http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm> (accessed October 20, 2008).
- 25 California Air Resources Board. (2008, October) Draft Proposed Regulatory Language For Semiconductor and Related Devices Operations. <http://www.arb.ca.gov/cc/high-GWPss/meetings/092908/SF6DraftRegulatorylanguage092308.pdf> (accessed October 20, 2008).
- 26 California Air Resources Board. (2008, September) Draft Proposed Regulation Order: Regulation for Sulfur Hexafluoride Use and Sales. <http://www.arb.ca.gov/cc/semiconductors/meetings/102308/proposedreg.pdf> (accessed October 15, 2008).
- 27 Connecticut's Governor's Steering Committee on Climate Change. Connecticut's Climate Change Action Plan 2005, Residential, Commercial and Industrial Sector, RA 34 – Identify Measures to Reduce High Global Warming Potential Gases. http://ctclimatechange.com/documents/RA_34_MeasurestoReduceHigh-GWPGases_CCCAP_2005.pdf (accessed October 15, 2008).
- 28 Illinois EPA. Illinois Climate Change Advisory Group. <http://www.epa.state.il.us/air/climatechange/> (accessed October 23, 2008).
- 29 Massachusetts Legislature. Chapter 298 of Session Law of 2008. <http://www.mass.gov/legis/laws/seslaw08/sl080298.htm> (accessed October 27, 2008).
- 30 New Jersey Legislature. Global Warming Response Act. http://www.njleg.state.nj.us/2006/Bills/AL07/112_PDF (accessed October 27, 2008).
- 31 New Jersey Department of Environmental Protection. (2008, March 13). New Jersey Greenhouse Gas Monitoring and Reporting Rule. Stakeholder Meeting Presentation. <http://www.nj.gov/globalwarming/pdf/StakeholderMeeting-051308.pdf> (accessed October 27, 2008).
- 32 Wisconsin Department of Natural Resources. Refrigerant Recovery Program. <http://dnr.wi.gov/air/compenf/refrig/index.html> (accessed October 27, 2008).
- 33 United Nations Environment Programme, HFC and PFC Task Force of the Technology and Economic Assessment Panel. (1999, October). The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol. http://ozone.unep.org/teap/Reports/Other_Task_Force/HFCPFC.pdf (accessed October 27, 2008).
- 34 United Nations Environment Programme, HFC and PFC Task Force of the Technology and Economic Assessment Panel. (1999, October). The Implications to the Montreal Protocol of the Inclusion of HFCs and PFCs in the Kyoto Protocol, page 15. http://ozone.unep.org/teap/Reports/Other_Task_Force/HFCPFC.pdf (accessed October 27, 2008).
- 35 European Commission. Fluorinated Greenhouse Gases. http://ec.europa.eu/environment/climat/fluor/index_en.htm (accessed October 28, 2008).
- 36 European Commission. Fluorinated Greenhouse Gases, Actions. http://ec.europa.eu/environment/climat/fluor/actions_en.htm (accessed October 28, 2008).
- 37 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: EU; Austria; Denmark - Regulation on F-gases; Austrian phase out and reduction programme; Danish tax on the import and use. http://www.senternovem.nl/mmfiles/EU%20Austria%20Denmark.doc_tcm24-241029.pdf (accessed October 28, 2008).
- 38 Ibid.
- 39 Danish Ministry of the Environment, Environmental Protection Agency. Fact sheet No. 46: Industrial greenhouse gases: HFCs, PFCs and SF₆. http://www.mst.dk/English/Chemicals/Legislation/Fact_sheets/Fachtsheet_no_46.htm (accessed October 28, 2008).
- 40 Danish Ministry of the Environment, Environmental Protection Agency. Fact sheet No. 46: Industrial greenhouse gases: HFCs, PFCs and SF₆.

-
- http://www.mst.dk/English/Chemicals/Legislation/Fact_sheets/Fachtsheet_no_46.htm (accessed October 28, 2008).
- 41 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: EU; Austria; Denmark - Regulation on F-gases; Austrian phase out and reduction programme; Danish tax on the import and use. http://www.senternovem.nl/mmfiles/EU%20Austria%20Denmark.doc_tcm24-241029.pdf (accessed November 3, 2008).
- 42 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: EU; Austria; Denmark - Regulation on F-gases; Austrian phase out and reduction programme; Danish tax on the import and use. http://www.senternovem.nl/mmfiles/EU%20Austria%20Denmark.doc_tcm24-241029.pdf (accessed November 3, 2008).
- 43 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: EU; Austria; Denmark - Regulation on F-gases; Austrian phase out and reduction programme; Danish tax on the import and use. http://www.senternovem.nl/mmfiles/EU%20Austria%20Denmark.doc_tcm24-241029.pdf (accessed November 3, 2008).
- 44 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: Norway - Import tax on HFC and PFC. http://www.senternovem.nl/mmfiles/Norway.doc_tcm24-241042.pdf (accessed November 4, 2008).
- 45 SenterNovem, Dutch Ministry of Economic Affairs. ROB International Web Page. <http://www.senternovem.nl/Robinternational/Index.asp> (accessed November 4, 2008).
- 46 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: Netherlands - HFC 'after'-incineration when producing HCFC. http://www.senternovem.nl/mmfiles/Netherlands%202.doc_tcm24-241035.pdf (accessed November 5, 2008).
- 47 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: Netherlands - HFC 'after'-incineration when producing HCFC. http://www.senternovem.nl/mmfiles/Netherlands%202.doc_tcm24-241035.pdf (accessed November 5, 2008).
- 48 Iceland Ministry for the Environment. (February 2007). Iceland's Climate Change Strategy, p 35. http://eng.umhverfisraduneyti.is/media/PDF_skrar/Stefnumorkun_i_loftslagsmalum_enlokagerd.pdf (accessed November 3, 2008).
- 49 Swedish EPA, Climate Committee. (2008, March). Assessment of Swedish Climate Policy (Svensk klimatpolitik). <http://www.regeringen.se/content/1/c6/09/96/94/8393cd02.pdf#page=38> (accessed November 3, 2008).
- 50 Committee on Climate Change. (2008, December 1) Building a low-carbon economy - the UK's contribution to tackling climate change. 335 <http://www.theccc.org.uk/reports/> (accessed November 3, 2008).
- 51 Committee on Climate Change. (2008, December 1) Building a low-carbon economy - the UK's contribution to tackling climate change. 356. <http://www.theccc.org.uk/reports/> (accessed November 4, 2008).
- 52 Committee on Climate Change. (2008, December 1) Building a low-carbon economy - the UK's contribution to tackling climate change. 359. <http://www.theccc.org.uk/reports/>. (accessed November 4, 2008).
- 53 SenterNovem, Dutch Ministry of Economic Affairs. (2007, September 27). Inspiration beyond CO₂ reduction, Case: Japan - Voluntary industrial programs on F-gases. http://www.senternovem.nl/mmfiles/Japan.doc_tcm24-241032.pdf (accessed November 4, 2008).
- 54 United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. Washington, D.C.: Office of Atmospheric Programs (6207J) EPA 430-R-06-005.
- 55 United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. 1-13.

-
- ⁵⁶ Schwaab, K., Dettling, F., Bernhardt, D., Elsner, C., Sartorius, R., Reimann, K., Remus, R., and Plehn, W. 2004. Fluorinated greenhouse gases in products and processes: Technical climate protection measures. Report of the Federal Environmental Agency. Berlin, Germany: Federal Environmental Agency.
- ⁵⁷ Refrigeration diagram <http://www.geo4va.vt.edu/A3/refrigeration-cycle.gif> (accessed on December 11, 2008).
- ⁵⁸ This description was adapted from a presentation by *Ir. Kelvin Tam* Department of Mechanical Engineering The University of Hong Kong Refrigeration Systems. <http://www.hku.hk/mech/msc-courses/MEBS6006/index.html> (accessed on December 11, 2008).
- ⁵⁹ UBA – Umweltbundesamt. 2004. *Fluorinated greenhouse gases in products and processes – Technical climate protection measures*. Berlin: German Federal Environmental Agency. <http://www.umweltbundesamt.org/fpdf-l/2791.pdf> (accessed on October 23, 2008).
- ⁶⁰ UBA – Umweltbundesamt. 2004. *Fluorinated greenhouse gases in products and processes – Technical climate protection measures*. Berlin: German Federal Environmental Agency. 22 <http://www.umweltbundesamt.org/fpdf-l/2791.pdf> (accessed on October 23, 2008).
- ⁶¹ UBA – Umweltbundesamt. 2004. *Fluorinated greenhouse gases in products and processes – Technical climate protection measures*. Berlin: German Federal Environmental Agency. 23 <http://www.umweltbundesamt.org/fpdf-l/2791.pdf> (accessed on October 23, 2008).
- ⁶² Ibid.
- ⁶³ International Energy Agency. 2001. Abatement of emissions of other greenhouse gases - engineered chemicals. Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom.
- ⁶⁴ Gauger, D.C., Shapiro, H.N. & Pate, M.B. 1995. Alternative technologies for refrigeration and air-conditioning applications. EPA/600/SR-95/066.
- ⁶⁵ Gauger, D.C., Shapiro, H.N. & Pate, M.B. 1995. Alternative technologies for refrigeration and air-conditioning applications. EPA/600/SR-95/066. 3.
- ⁶⁶ Walker, D. Low-charge refrigeration for supermarkets. Walker, D.H., “Low-charge refrigeration for supermarkets”, IEA Heat Pump Center Newsletter, Sittard, the Netherlands, Volume 18, No. 1/2000. 2.
- ⁶⁷ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁶⁸ Walker, D. 2000. Low-charge refrigeration for supermarkets. IEA Heat Pump Center Newsletter, Sittard, the Netherlands, 18(1); 2.
- ⁶⁹ Walker, D. 2000. Low-charge refrigeration for supermarkets. IEA Heat Pump Center Newsletter, Sittard, the Netherlands, 18(1); 2-3.
- ⁷⁰ ICF Consulting. 2005. *Emission reduction opportunities for non-CO2 greenhouse gases in California*. California Energy Commission, CEC-500-2005-121.
- ⁷¹ Walker, D. 2000. Low-charge refrigeration for supermarkets. IEA Heat Pump Center Newsletter, Sittard, the Netherlands, 18(1); 4.
- ⁷² Knowles, M., 2003. Sustainability characteristics of SPF roofing & insulation systems. *Modern Materials*, November; 20.
- ⁷³ Walker, D. 2000. Low-charge refrigeration for supermarkets. IEA Heat Pump Center Newsletter, Sittard, the Netherlands, 18(1); 4.
- ⁷⁴ Walker, D. 2000. Low-charge refrigeration for supermarkets. IEA Heat Pump Center Newsletter, Sittard, the Netherlands, 18(1); 5.
- ⁷⁵ Calm, J.M. 2002. Options and outlook for chiller refrigerant. *International Journal of Refrigeration*, 25, 705-715.
- ⁷⁶ 100 years of ammonia synthesis: how a single patent changed the world. http://www.ceh.ac.uk/news/news_archive/2008_news_item_35.html (accessed on December 9, 2008).
- ⁷⁷ Information on the propane market was derived from National Energy Information Center (2008) Propane Prices: What Consumers Should Know. DOE/EIA-X045. <http://www.eia.doe.gov/bookshelf/brochures/propane/> (accessed on November 18, 2008).
- ⁷⁸ Production of DME from Biomass and utilization as fuel for transport and for industrial use. <http://www.biodme.eu/> (accessed on December 10, 2008).

-
- ⁷⁹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 7-17 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁸⁰ Monthly average propane and butane prices – Canada. https://services.shell.ca/postedprices/pb_pricedetail.jsp?p=MjE0NA==&d=RkM0IEAgRWRtb250b24= (accessed on December 11, 2008).
- ⁸¹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 7-17 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁸² United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV - 27
- ⁸³ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV-55
- ⁸⁴ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 7-14 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁸⁵ Went-Tien Tsai. 2005. An overview of environmental hazards and exposure risk of hydrofluorocarbons (HFCs). *Chemosphere*, 61; 1541.
- ⁸⁶ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 7-14 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008)..
- ⁸⁷ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 7-16 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008)..
- ⁸⁸ The Alliance for Responsible Atmospheric Policy. Vehicle Air Conditioning: A Working Example. <http://www.arap.org/docs/vac.html> (accessed on November 19, 2008).
- ⁸⁹ Lutsey, Nicolas. “Prioritizing Climate Change Mitigation Alternatives: Comparing Transportation Technologies to Options in Other Sectors. Institute of Transportation Studies,” (Ph.D. dissertation USC-ITS-RR-08-15, University of California – Davis, 2008).
- ⁹⁰ European Fluorocarbons Technical Committee. Air conditioning – Mobile http://www.fluorocarbons.org/en/applications/air_conditioning.html#c1 (accessed on December 23, 2008).
- ⁹¹ Feske, Bert (October 2004). The use of Saytex RB-9130/9170 low viscosity brominated flame retardant polyols in HFC-245fa and high water formulations. Las Vegas, NV: Alliance for the Polyurethane Industry Technical Conference.
- ⁹² United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 9-2. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁹³ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).U.S., High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions – June 2001; 9-6.
- ⁹⁴ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).U.S., High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions – June 2001; 9-7.
- ⁹⁵ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV-80.
- ⁹⁶ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 9-15 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ⁹⁷ Ibid.
- ⁹⁸ Ibid.

-
- ⁹⁹ Ibid.
- ¹⁰⁰ United States Department of Energy Fact Sheet on Insulation. http://www.ornl.gov/sci/roofs+walls/insulation/ins_02.html (accessed on December 18, 2008).
- ¹⁰¹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 9-8 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹⁰² Ibid.
- ¹⁰³ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 9-12 <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹⁰⁴ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 11-2. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹⁰⁵ Went-Tien Tsai 2005. An overview of environmental hazards and exposure risk of hydrofluorocarbons (HFCs). *Chemosphere*, 61; 1541.
- ¹⁰⁶ Ibid.
- ¹⁰⁷ Ibid.
- ¹⁰⁸ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV-123
- ¹⁰⁹ Ibid.
- ¹¹⁰ Ibid.
- ¹¹¹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 11-4. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹¹² United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV-169.
- ¹¹³ Ibid.
- ¹¹⁴ Iskenderova, Kamilla. "Cleaning process in high density plasma chemical vapor deposition reactor." Ph.D. Diss. A.J. Drexel Plasma Institute, 2003.
- ¹¹⁵ Robert Doering and Yoshio Nishi. *Handbook of Semiconductor Manufacturing Technology*. Boca Raton, FL: CRC Press, 2008.
- ¹¹⁶ Misra, A., Sees, J., Hall, L., Levy, R.A., Zaitsev, V.B., Aryusook, K., Ravindranath, C., Sigal, V., Kesari, S. and Rufin, D. 1998. Plasma Etching of dielectric films using the non-global-warming gas CF₃I. *Materials Letters*, 34: 415-419.
- ¹¹⁷ Ibid.
- ¹¹⁸ National Research Council. Iodotrifluoromethane: Toxicity Review. Washington, DC: National Academy Press, 2004.
- ¹¹⁹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 6-3. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹²⁰ International Energy Agency. Building the Cost Curves for the Industrial Sources of Non-CO₂ Greenhouse Gases. Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
- ¹²¹ United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 6-3. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹²² Alternatives evaluation for the semiconductor industry from <http://www.arb.ca.gov/cc/non-co2-clearinghouse/technology/c-3-4.pdf> (accessed on December 23, 2008).
- ¹²³ See U.S. Climate Technology Program. Technology Options for the Near and Long Term, U.S. Department of Energy, <http://www.climate-technology.gov/index.htm>, August 2005. and United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- ¹²⁴ Alternatives evaluation for the semiconductor industry from <http://www.arb.ca.gov/cc/non-co2-clearinghouse/technology/c-3-4.pdf> (accessed on December 23, 2008)

- 125 U.S. Climate Technology Program. Technology Options for the Near and Long Term, U.S. Department of Energy, <http://www.climate-technology.gov/index.htm>, August 2005.
- 126 Alternatives evaluation for the semiconductor industry from <http://www.arb.ca.gov/cc/non-co2-clearinghouse/technology/c-3-4.pdf> (accessed on December 23, 2008)
- 127 U.S. Climate Technology Program. Technology Options for the Near and Long Term, U.S. Department of Energy, <http://www.climate-technology.gov/index.htm>, August 2005.
- 128 International Energy Agency. Building the Cost Curves for the Industrial Sources of Non-CO₂ Greenhouse Gases. Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
- 129 Alternatives evaluation for the semiconductor industry from <http://www.arb.ca.gov/cc/non-co2-clearinghouse/technology/c-3-5.pdf> (accessed on December 23, 2008)
- 130 United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- 131 D. Cowles, "Oxide Etch Tool Emissions Comparison for C₅F₈ and C₄F₈ Process Recipes," *A Partnership for PFC Emissions Reductions*, SEMICON Southwest, Austin, Texas, Oct. 18, 1999. and Hokari, Y. 1999. *An ASET New Program for PFC Emission Reduction in Dry-Etching Process*. Association of Super-Advanced Electronics Technologies (ASET).
- 132 United States Environmental Protection Agency. 2001. U.S. High-GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. 6-4. <http://www.epa.gov/highhigh-GWP/pdfs/high-GWPcover.pdf> (accessed on December 3, 2008).
- 133 M. Mocella, "PFC Recovery: Issues, Technologies and Considerations for Post-Recovery Processing," *Global Semiconductor Industry Conference on Perfluorocompound Emissions Control*, Monterey, Calif., April 7, 1998.
- 134 United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV – 150.
- 135 Intergovernmental Panel on Climate Change – Direct GWP. http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/248.htm (accessed on December 21, 2008).
- 136 Olivier, J.G.J. and Baker, J. Historical emissions of HFCs, PFCs and SF₆ 1950-1995. Draft RIVM report. RIVM Bilthoven (The Netherlands), 1999.
- 137 SF₆ Emission Reduction Partnership for Electric Power Systems <http://www.epa.gov/electricpower-sf6/basic.html> (accessed on December 30, 2008).
- 138 Minnesota Department of Commerce. The Minnesota Utility Data Book: A Reference Guide to Minnesota Electric and Natural-Gas Utilities 1965-2005. http://www.state.mn.us/mn/externalDocs/Commerce/Utility_Data_Book_1965-2000_030603120425_UtilityDataBook65thru05.pdf (accessed on January 2, 2009).
- 139 United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV-187.
- 140 Ibid.
- 141 Smeaton, Robert W. (ed). *Switchgear and Control Handbook*. New York: Mc Graw Hill, 1997.
- 142 United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. IV – 206.
- 143 SF₆ Emissions from Magnesium from Good Practices Guidance and Uncertainty Management in National Greenhouse Gas Inventories. http://www.climatevision.gov/sectors/magnesium/pdfs/magnesium_sf6emissions.pdf (accessed on December 3, 2008).
- 144 United States Environmental Protection Agency. Alternatives to SF₆ for Magnesium Melt Protection. EPA-430-R-06-007. 2006. http://www.epa.gov/magnesium-sf6/documents/magbrochure_english.pdf (accessed on December 22, 2008).
- 145 Minnesota Climate Change Advisory Group, 2008. Final Report. A Report to the Minnesota Legislature. Saint Paul, MN. Appendix F-18.

-
- ¹⁴⁶ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. F-19 – F-20.
- ¹⁴⁷ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. F-20.
- ¹⁴⁸ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. F-19.
- ¹⁴⁹ United States Environmental Protection Agency. 2006. Global Mitigation of Non-CO₂ Greenhouse Gases. F-20.
- ¹⁵⁰ Review of state greenhouse gas reporting thresholds.
http://www.deq.state.or.us/aq/climate/docs/121707_reportTrackChanges.pdf (accessed on January 23, 2009).

List of Acronyms

\$/tCO ₂ e	dollars per ton of carbon dioxide equivalent
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAU	business as usual
BMPs	best management practices
CAA	Clean Air Act
CARB	California Air Resources Board
CFC	chlorofluorocarbon
CH ₄	methane
CO ₂	carbon dioxide
COP	coefficient of performance
CVD	chemical vapor deposition
EE	energy efficiency
EPA	[United States] Environmental Protection Agency
EU	European Union
F-gases	fluorinated gases
GHG	greenhouse gas
GIS	gas insulated switchgear
GRE	Great River Energy
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HGWP	high global warming potential (or high-GWP)
IPCC	Intergovernmental Panel on Climate Change
LCCP	life cycle climate performance
LCD	liquid carbon dioxide
MAC	mobile air conditioning
MCCAG	Minnesota Climate Change Advisory Group
MMBtu	million British thermal units
MMGPY	million gallons per year
MMtCO ₂ e	million metric tons of carbon dioxide equivalent
MnDOC	Minnesota Department of Commerce
MnTAP	Minnesota Technical Assistance Program
MPCA	Minnesota Pollution Control Agency
Mt	metric ton
MtCO ₂ e	metric tons of carbon dioxide equivalent
N	nitrogen
N ₂ O	nitrous oxide
NF ₃	
NGEA	Next Generation Energy Act
NGEI	Next Generation Energy Initiative
NO _x	nitrogen oxides
NPV	net present value

O&M	operations and maintenance
ODS	ozone-depleting substance
PFC	perfluororocarbon
R&D	research and development
SF ₆	sulfur hexafluoride
SNAP	Significant New Alternatives Program
SO ₂	sulfur dioxide
TFSS	total fire suppression system
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
VOC	volatile organic compound

Glossary of Climate Change Terms¹

Aerosols: Solid or liquid particles suspended within the atmosphere (see "sulfate aerosols" and "black carbon aerosols").

Anthropogenic Emissions: Emissions of greenhouse gasses resulting from human activities.

Baselines: The baseline estimates of population, GDP, energy use and hence resultant greenhouse gas emissions without climate policies, determine how big a reduction is required, and also what the impacts of climate change without policy will be.

Carbon Dioxide (CO₂): CO₂ is a colorless, odorless, non-poisonous gas that is a normal part of the ambient air. Of the six greenhouse gases normally targeted, CO₂ contributes the most to human-induced global warming. Human activities such as fossil fuel combustion and deforestation have increased atmospheric concentrations of CO₂ by approximately 30 percent since the industrial revolution. CO₂ is the standard used to determine the "global warming potentials" (GWPs) of other gases. CO₂ has been assigned a 100-year GWP of 1 (i.e., the warming effects over a 100-year time frame relative to other gases).

Carbon Dioxide Equivalent (CO₂e): Carbon Dioxide Equivalent (CO₂e). The emissions of a gas, by weight, multiplied by its "global warming potential."

Carbon Sinks: Processes that remove more carbon dioxide from the atmosphere than they release. Both the terrestrial biosphere and oceans can act as carbon sinks.

Chlorofluorocarbons (CFCs): CFCs are synthetic industrial gases composed of chlorine, fluorine, and carbon. They have been used as refrigerants, aerosol propellants, cleaning solvents and in the manufacture of plastic foam. There are no natural sources of CFCs. CFCs have an atmospheric lifetime of decades to centuries, and they have 100-year "global warming potentials" thousands of times that of CO₂, depending on the gas. In addition to being greenhouse gases, CFCs also contribute to ozone depletion in the stratosphere and are controlled under the Montreal Protocol.

Climate: The long-term average weather of a region including typical weather patterns, the frequency and intensity of storms, cold spells, and heat waves. Climate is not the same as weather.

Climate Change: Refers to changes in long-term trends in the average climate, such as changes in average temperatures. In IPCC usage, climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. In UNFCCC usage, climate change refers to a change in climate that is attributable directly or indirectly to human activity that alters atmospheric composition.

Discounting: The process that reduces future costs and benefits to reflect the time value of money and the common preference of consumption now rather than later.

Emissions: The release of substances (e.g., greenhouse gases) into the atmosphere.

¹ Modified after the Pew Charitable Trust report on Climate Change. Source: http://www.pewclimate.org/global-warming-basics/full_glossary/glossary.php

European Community: As a regional economic integration organization, the European Community can be and is a Party to the UNFCCC; however, it does not have a separate vote from its members (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxemburg, the Netherlands, Portugal, Spain, Sweden, and the United Kingdom).

Global Warming: The progressive gradual rise of the Earth's average surface temperature thought to be caused in part by increased concentrations of GHGs in the atmosphere.

Global Warming Potential (GWP): A system of multipliers devised to enable warming effects of different gases to be compared. The cumulative warming effect, over a specified time period, of an emission of a mass unit of CO₂ is assigned the value of 1. Effects of emissions of a mass unit of non-CO₂ greenhouse gases are estimated as multiples. For example, over the next 100 years, a gram of methane (CH₄) in the atmosphere is currently estimated as having 23 times the warming effect as a gram of carbon dioxide; methane's 100-year GWP is thus 23. Estimates of GWP vary depending on the time-scale considered (e.g., 20-, 50-, or 100-year GWP), because the effects of some GHGs are more persistent than others.

Greenhouse Effect: The insulating effect of atmospheric greenhouse gases (e.g., water vapor, carbon dioxide, methane, etc.) that keeps the Earth's temperature about 60°F warmer than it would be otherwise.

Greenhouse Gas (GHG): Any gas that contributes to the "greenhouse effect."

HGWP (High Global Warming Potential): Some industrially produced gases such as sulfur hexafluoride (SF₆), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) have extremely high GWPs. Emissions of these gases have a much greater effect on global warming than an equal emission (by weight) of the naturally occurring gases. Most of these gases have GWPs of 1,300 - 23,900 times that of CO₂. These GWPs can be compared to the GWPs of CO₂, CH₄, and N₂O which are presently estimated to be 1, 23 and 296, respectively.

Hydrofluorocarbons (HFCs): HFCs are synthetic industrial gases, primarily used in refrigeration and semi-conductor manufacturing as commercial substitutes for chlorofluorocarbons (CFCs). There are no natural sources of HFCs. The atmospheric lifetime of HFCs is decades to centuries, and they have 100-year "global warming potentials" thousands of times that of CO₂, depending on the gas. HFCs are among the six greenhouse gases to be curbed under the Kyoto Protocol.

Intergovernmental Panel on Climate Change (IPCC): The IPCC was established in 1988 by the World Meteorological Organization and the UN Environment Programme. The IPCC is responsible for providing the scientific and technical foundation for the United Nations Framework Convention on Climate Change (UNFCCC), primarily through the publication of periodic assessment reports (see "Second Assessment Report" and "Third Assessment Report").

Kyoto Protocol: An international agreement adopted in December 1997 in Kyoto, Japan. The Protocol sets binding emission targets for developed countries that would reduce their emissions on average 5.2 percent below 1990 levels.

Methane (CH₄): CH₄ is among the six greenhouse gases to be curbed under the Kyoto Protocol. Atmospheric CH₄ is produced by natural processes, but there are also substantial emissions from human activities such as landfills, livestock and livestock wastes, natural gas and petroleum systems, coalmines, rice fields, and wastewater treatment. CH₄ has a relatively short atmospheric lifetime of approximately 10 years, but its 100-year GWP is currently estimated to be approximately 23 times that of CO₂.

Montreal Protocol: (on Substances that Deplete the Ozone Layer) An international agreement that entered into force in January 1989 to phase out the use of ozone-depleting compounds such as methyl chloroform, carbon tetrachloride, and CFCs. CFCs are potent greenhouse gases which are not regulated by the Kyoto Protocol since they are covered by the Montreal Protocol.

Perfluorocarbons (PFCs): PFCs are among the six types of greenhouse gases to be curbed under the Kyoto Protocol. PFCs are synthetic industrial gases generated as a by-product of aluminum smelting and uranium enrichment. They also are used as substitutes for CFCs in the manufacture of semiconductors. There are no natural sources of PFCs. PFCs have atmospheric lifetimes of thousands to tens of thousands of years and 100-year GWPs thousands of times that of CO₂, depending on the gas.

ppm or ppb: Abbreviations for “parts per million” and “parts per billion,” respectively - the units in which concentrations of greenhouse gases are commonly presented. For example, since the pre-industrial era, atmospheric concentrations of carbon dioxide have increased from 270 ppm to 370 ppm.

Radiative Forcing: The term radiative forcing refers to changes in the energy balance of the earth-atmosphere system in response to a change in factors such as greenhouse gases, land-use change, or solar radiation. The climate system inherently attempts to balance incoming (e.g., light) and outgoing (e.g. heat) radiation. Positive radiative forcings increase the temperature of the lower atmosphere, which in turn increases temperatures at the Earth's surface. Negative radiative forcings cool the lower atmosphere. Radiative forcing is most commonly measured in units of watts per square meter (W/m²).

Sequestration: Opportunities to remove atmospheric CO₂, either through biological processes (e.g. plants and trees), or geological processes through storage of CO₂ in underground reservoirs.

Sinks: Any process, activity or mechanism that results in the net removal of greenhouse gases, aerosols, or precursors of greenhouse gases from the atmosphere.

Source: Any process or activity that results in the net release of greenhouse gases, aerosols, or precursors of greenhouse gases into the atmosphere.

Stratosphere: The region of the Earth's atmosphere 10-50 km above the surface of the planet.

Substitution: The economic process of trading off inputs and consumption due to changes in prices arising from a constraint on greenhouse gas emissions. How the extremely flexible U.S. economy adapts to available substitutes and/or finds new methods of production under a greenhouse gas constraint will be critical in minimizing overall costs of reducing emissions.

Sulfur Hexafluoride (SF₆): SF₆ is among the six types of greenhouse gases to be curbed under the Kyoto Protocol. SF₆ is a synthetic industrial gas largely used in heavy industry to insulate high-voltage equipment and to assist in the manufacturing of cable-cooling systems. There are no natural sources of SF₆. SF₆ has an atmospheric lifetime of 3,200 years. Its 100-year GWP is currently estimated to be 22,200 times that of CO₂.

Technological Change: How much technological change will be additionally induced by climate policies is a crucial, but not well quantified, factor in assessing the costs of long-term mitigation of greenhouse gas emissions.

Trace Gas: A term used to refer to gases found in the Earth's atmosphere other than nitrogen, oxygen, argon and water vapor. When this terminology is used, carbon dioxide, methane, and nitrous oxide are

classified as trace gases. Although trace gases taken together make up less than one percent of the atmosphere, carbon dioxide, methane and nitrous oxide are important in the climate system. Water vapor also plays an important role in the climate system; its concentrations in the lower atmosphere vary considerably from essentially zero in cold dry air masses to perhaps 4 percent by volume in humid tropical air masses.

Troposphere: The region of the Earth's atmosphere 0-10 km above the planet's surface.

Uncertainty: Uncertainty is a prominent feature of the benefits and costs of climate change. Decision makers need to compare risk of premature or unnecessary actions with risk of failing to take actions that subsequently prove to be warranted. This is complicated by potential irreversibilities in climate impacts and long term investments.

Water Vapor (H₂O): Water vapor is the primary gas responsible for the greenhouse effect. It is believed that increases in temperature caused by anthropogenic emissions of greenhouse gases will increase the amount of water vapor in the atmosphere, resulting in additional warming (see "positive feedback").

Weather: Describes the short-term (i.e., hourly and daily) state of the atmosphere. Weather is not the same as climate.