The Woodrow Wilson School's Graduate Policy Workshop

Complements to Carbon

Opportunities for Near-Term Action on Non-CO_2 Climate Forcers

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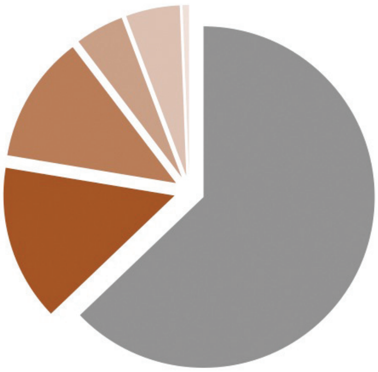
January 2011



Acknowledgements

The authors thank the many experts they consulted during the preparation of this report:

Stephen Andersen, *Technology and Economic Assessment Panel, Montreal Protocol*
Steve Anderson, *Refrigerants Australia*
Atul Bagai, *United Nations Environment Programme*
Bai Tiejun, *Honeywell*
Tom Batchelor, *TouchDown Consulting*
Akshay Bellare, *Honeywell*
Louis Bono, *U.S. Mission to the EU, U.S. State Department*
Payam Bozorgchami, *California Energy Commission*
Jeffries Brigginshaw, *Trans Atlantic Business Dialogue*
Cao Qiyong, *China GreenTech Institute*
Suely Carvalho, *United Nations Development Programme*
Jenny Chu, *Azure*
Dennis Clare, *Institute for Governance and Sustainable Development*
Ana Unruh Cohen, *House Select Committee on Energy Independence and Global Warming*
Bart Croes, *California Air Resources Board*
Amy Dickie, *California Environmental Associates*
Dick Dong, *Dupont*
David Doniger, *Natural Resources Defense Council*
Rick Duke, *U.S. Department of Energy*
Ottmar Edenhofer, *Intergovernmental Panel on Climate Change*
Jae Edmunds, *Pacific Northwest National Laboratory*
Daniel Enking, *Chinese Academy of Sciences*
Axel Friedrich, *Former Head of German Environment Ministry*
Haley Gilbert, *Lawrence Berkeley National Laboratory*
Rachel Goldstein, *U.S. Environmental Protection Agency*
Marco Gonzalez, *Ozone Secretariat, United Nations*
Peter Grabiel, *Institute for Governance and Sustainable Development*
Peter Gray, *McKenna Long & Aldridge LLP*
Sherry Hao, *Cool Roof Rating Council*
David Harmon, *European Commission Research, Innovation & Science Office*
Brent Hoare, *Green Cooling Association*
Hu Yuhong, *National Center for International Cooperation in Work Safety*
Drussilla Hufford, *U.S. Environmental Protection Agency*
Holmes Hummel, *U.S. Department of Energy*
Jiang Kejun, *Energy Research Institute*
Jing Cao, *Qinghua Center for China and the World Economy, Department of Economics*
Daniel Klingenfeld, *Potsdam Institute for Climate*
Bob Kopp, *U.S. Department of Energy*
Tom Kram, *Intergovernmental Panel on Climate Change*
Lambert Kuijpers, *Refrigerants Technical Committee*
Marc LaFrance, *U.S. Department of Energy*
Ronnen Levinson, *Lawrence Berkeley National Laboratory*
Li Zheng, *Tsinghua-BP Clean Energy Research and Education Center*
Alvin Lin, *Natural Resources Defense Council, Beijing*
Lin Junda, *China GreenTech Institute*
Peter Linton, *Burson Marsteller*
Liu Wenge, *China Coal Institute*
Alan Lloyd, *International Council on Clean Transportation*
Simon Marr, *German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety*
Karen Massin, *Burson Marsteller*
Janos Mate, *Greenpeace International Climate Campaign*
David McCabe, *Clean Air Task Force*
Andrew McConville, *White House Office of Energy and Climate Change*
Mack McFarland, *DuPont Chemicals and Fluoroproducts*
William McQuade, *Johnson Controls*
Surabi Menon, *Lawrence Berkeley National Laboratory*
Ray Minjares, *International Council on Clean Transportation*
Kevin Mo, *The Energy Foundation*
Terry Mo Haocheng, *Honeywell*
Jeff Moe, *Ingersoll Rand*
Niu Yongming, *Honeywell*
Eirik Nordheim, *European Aluminum Association*
Christianna Papazahariou, *Shecco*
Melvin Pomerantz, *Lawrence Berkeley National Laboratory*
Sally Rand, *U.S. Environmental Protection Agency*
A. R. Ravishankara, *NOAA Earth System Research Laboratory*
Daniel Reifsnyder, *U.S. Department of State*
Arthur Rosenfeld, *Lawrence Berkeley National Laboratory and University of California, Berkeley*
Sang Fengyu, *China Coal Institute*
Marcus Sarofim, *U.S. Environmental Protection Agency*
Hans Joachim Schellnhuber, *Potsdam Institute for Climate*
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Mark Stanga, *Competition Advocates, LLC*
Jonah Steinbuck, *House Select Committee on Energy Independence and Global Warming*
Evelyn Swain, *U.S. Environmental Protection Agency*
Kristen Taddonio, *U.S. Environmental Protection Agency*
Helen Tope, *Energy International Australia*
Christie Ulman, *U.S. Department of Energy*
Tomas Velghe, *European Commission Directorate-General for the Environment*
Vance Wagner, *Ministry of Environmental Protection, Beijing*
Wang Baiyu, *Capital Carbon*
Fionnuala Walravens, *Environmental Investigation Agency*
John Weyant, *Stanford University*
Erik White, *California Air Resources Board*
Catherine Witherspoon, *ClimateWorks Foundation*
Philip Wong, *Suntech*
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Zhou Weiqi, *National Center for International Cooperation in Work Safety*

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Methodology

This report was researched and written by a group of Master in Public Affairs students at the Woodrow Wilson School, and Ph.D. candidates from the Woodrow Wilson School, the Program in Atmospheric and Oceanic Sciences, and the Departments of Chemical Engineering, Civil and Environmental Engineering, and Geosciences at Princeton University. Princeton University atmospheric scientist Denise Mauzerall facilitated the project as part of the annual graduate policy workshop program. The goal of the workshop program is for students to contribute to addressing critical policy problems for real clients. This particular workshop arose out of the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency's (EPA) desire to develop a compendium of fast-action mitigation strategies for non-CO_2 climate forcers. The group set out to address that need and hopes it has succeeded in offering recommendations that will be useful to DOE and EPA, as well as other interested bodies. In developing the report, the group first met with the DOE Deputy Assistant Secretary for Climate Policy and other experts at DOE and EPA to discuss their interests and needs. Over the following weeks, the group reviewed the latest science behind non-CO_2 climate forcers and researched possible mitigation strategies. The latter included discussions with almost 100 experts and stakeholders from government agencies, international organizations, corporations, business networks, academia, and advocacy groups. Through careful research and deliberation, the group evaluated the environmental impacts of non-CO_2 forcers and calculated the costs and benefits of certain mitigation strategies, before providing a suite of policy opportunities focused on reducing non-CO_2 climate forcers both domestically and internationally.

The Woodrow Wilson School of Public and International Affairs, founded at Princeton University in 1930, provides an interdisciplinary program that prepares undergraduate and graduate students for careers in public and international affairs. The school is one of the world's premier academic and research institutions devoted to public and international affairs. The views expressed in this report are the views of the authors and do not represent the views of Princeton University, the Woodrow Wilson School, the Department of Energy, the Environmental Protection Agency, or those who provided advice. Any errors of fact are the responsibility of the authors.

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Executive Summary

International and domestic efforts to prevent further anthropogenic interference in the climate system have, to date, primarily focused on options for reducing carbon dioxide (CO_2) emissions. While CO_2 is the largest driver of global warming, non-CO_2 climate forcers—defined as any gas, particle, or effect that contributes to climate change—are responsible for almost half of the total human-caused radiative forcing in the atmosphere. It will not be possible to fully address the challenge of anthropogenic climate change without addressing non-CO_2 climate forcers. Although emissions of other climate forcers are lower than those of CO_2, many have much higher global warming potentials (GWPs) and high projected emissions growth rates. There are fast-action opportunities that can be taken now, under existing authority, to address these forcers. Action on non-CO_2 climate forcers could provide a vital buffer in avoiding the worst effects of climate change as the global community struggles to develop strong and effective action on CO_2.

This report outlines an array of policy opportunities that the U.S. government can consider for reducing the impact of non-CO_2 climate forcers. Three main categories of climate forcers are reviewed in this report:

- **Non-CO_2 greenhouse gases (GHGs):** methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and emissions from banks of ozone-depleting substances (ODSs);
- **Black carbon**; and
- **Surface reflective and emissive properties:** reflectivity and emissivity of roofs and pavements.

The report investigates each climate forcer in detail, offers an assessment of its climate impact, reviews current policies with respect to the forcer, and identifies policy opportunities. The policy options presented encompass both domestic and international opportunities for the U.S. government to mitigate non-CO_2 climate forcing, emphasizing strategies possible under current federal authority and fast-action strategies. Fast-action strategies are defined as those that can begin in two to three years, be substantially implemented within five to ten years, and have the goal of producing the desired climate response within decades. The report focuses particularly on strategies that can be implemented by the U.S. Environmental Protection Agency (EPA) or the U.S. Department of Energy (DOE).

Policy opportunities

Policy opportunities are identified for each climate forcer, and a subset of top policy opportunities are selected based on the following criteria:

1. potential impact on the climate, including consideration of emissions growth rates,
2. speed of implementation,
3. maturity of technology,
4. cost to government,
5. cost to private sector, and
6. co-benefits.

Below is a brief description of key policies that meet these criteria. The first two opportunities apply across multiple non-CO_2 climate forcers. The section where each opportunity is discussed in greater detail is noted in parentheses. Case studies related to these opportunities are compiled in Appendix I, and further information on mitigation technology and costs is compiled in Appendix II. In addition, a list of all policy opportunities included in the report follows this executive summary.

Consideration of life cycle emissions (5.1a.): Specialty chemicals like HFCs, SF_6, PFCs and NF_3 are used in well-defined sectors and have a limited number of producers. For such chemicals, a "cradle to grave" life cycle emissions policy is recommended to reduce emissions during the entire use of the chemical, rather than at just one point in time.

Creation of a task force on non-CO_2 climate forcers in an appropriate international forum (5.1.b.): A task force on non-CO_2 climate forcers could provide a forum for countries to make voluntary commitments, exchange technical information on mitigation strategies and take coordinated action. Two possible arenas to catalyze cooperation around non-CO_2 climate forcers are the Major Economies Forum (MEF) and the Clean Energy Ministerial.

EPA regulation of methane emissions (4.1.4.a): Under the Clean Air Act, EPA could mandate the reduction of methane emissions from new stationary sources and certain existing facilities and/or mandate the use of methane emissions in a beneficial manner, such as the production of natural gas for energy supply. These regulations could build on existing landfill emissions regulations. The Canadian province of Alberta has successfully implemented strong policy to limit methane emissions from oil and gas production.

Establishment of N_2O performance standards under the Clean Air Act (4.2.4.a): N_2O is emitted in the production of nitric and adipic acid. Establishing an industrial standard based on the N_2O emissions rates from the best performing nitric and adipic acid plants would significantly reduce their emissions. This emulates the EU "average best 10 percent" policy for N_2O emissions from nitric acid plants.

Amendment of the Montreal Protocol to include N_2O (4.2.4.b): The Montreal Protocol, considered one of the most successful treaties to date, has the legal authority to control N_2O, given its ozone-depleting properties. The treaty has already acted explicitly to deliver a climate co-benefit by accelerating the phase-out of HCFCs in 2007. Proposing to control N_2O under the Montreal Protocol could offer the U.S. an opportunity to underscore its commitment to both stratospheric ozone protection and international climate policy.

Policy support for installation of diesel particulate filters in heavy-duty vehicles (4.3.4.a): Though U.S. regulations are greatly reducing emissions of particulate matter (PM) from new vehicles, older vehicles continue to emit large quantities of black carbon. EPA could support retrofitting heavy-duty diesel vehicles with particulate filters, which would reduce black carbon emissions. This support could involve enhancing EPA's Diesel Retrofit Technology Verification program to include information on best practices and examples of current retrofit programs.

International cooperation to address black carbon emissions from brick kilns (4.3.4.b): Black carbon emissions from this sector are significant and rapidly growing in many developing countries, responsible for close to 1 $GtCO_2e$ (GWP_{100}) of black carbon emissions. Production is concentrated in four countries: China, India, Pakistan, and Bangladesh. Negative net cost solutions exist, and agencies could work to support international cooperation to deploy existing mitigation technologies.

International cooperation to reduce black carbon emissions that reach "hot spots" (4.3.4.c): Both the Arctic and the Himalayas are black carbon "hot spots," meaning that black carbon emissions in and near these regions have a disproportionate effect on regional warming by darkening snow. As the Earth warms and activities in the Arctic and surrounding the Himalayas increase, regional cooperation will be needed to reduce black carbon emissions reaching these snow-covered regions.

DOE expansion and modification of Cash for Appliances program (4.4.4.a): Under the Cash for Appliances program, DOE allocated $300 million to states for the provision of consumer rebates for energy-efficient appliance purchases. Ozone depleting substances (ODSs) are contained in refrigerators and air conditioners and are strong greenhouse gases. This program can be expanded to require that states verify the safe disposal of the ODS contained in these appliances, something previously left up to states. Alternatively, DOE could restrict new rebates to purchases from retailers that are voluntary partners of EPA's Responsible Appliance Disposal program.

EPA withdrawal of SNAP approval of HFC-134a (4.5.4.a): HFC-134a is a strong greenhouse gas and is currently an approved alternative for ODS. Through the Significant New Alternatives Policy (SNAP) program, EPA could rescind the listing of HFC-134a as an approved alternative to ODS. Rescinding approval of HFC-134a would force manufacturers to substitute approved alternatives which have a smaller climate impact.

EPA and NHTSA incorporation of low-GWP refrigerant credits for medium-duty, heavy-duty, and off-road vehicle classes (4.5.4.b): In May 2010, EPA and the Department of Transportation set new fuel economy rules and GHG emissions standards for light duty vehicles, which include HFCs from mobile air conditioning. These standards could also be applied to other vehicle classes.

Engagement with large commercial cooling and retail food refrigeration industries to reduce HFC leakage in existing and new equipment (4.5.4.c): Refrigeration and cooling represents the sector with the largest abatement potential for HFCs. Agencies could engage suppliers, installers, and purchasers of cooling and refrigeration equipment to promote available technologies for leakage reduction, such as secondary loop or distributed systems with smaller coolant charge sizes.

International cooperation to identify financing for aluminum smelter retrofits (4.6.4.a): Older aluminum smelters are large sources of PFC emissions, which can be reduced through smelter retrofits. Because the primary hurdle to retrofit investment is upfront capital costs, international cooperation could help identify funding mechanisms for countries where new technology uptake is low. Retrofits save companies money through increased efficiency, creating a situation where retrofit loans could be paid back using cost savings from efficiency gains.

International cooperation to reduce PFC emissions from electronics and semiconductor manufacturing (4.6.4.b): PFC emissions from these industries have high projected growth rates, and PFCs are extremely long-lived. Governments, engaging with industry organizations like the World Semiconductor Council, could provide a forum to promote more comprehensive industry PFC emission reporting and best practice sharing regarding mitigation options.

Analysis of the potential scale of cost-effective cool roof deployment through federally funded building construction and roof repairs (4.9.4.a): The federal government funds building construction, repairs and energy efficiency improvements through a number of programs. Cool roofs could be included more systematically in these programs' guidelines. Quantifying the potential for cost-effective installation in these programs would be a first step toward towards greater cool roof deployment.

Promotion of high-albedo paving material use in applications with an unambiguous climate benefit (4.9.4.b): DOE's Cool Roofs Roadmap will help resolve outstanding questions about the life cycle climate impacts of paving materials. However, there are some applications where life cycle concerns do not appear to apply, such as parking lots and roads with low heavy-duty vehicle traffic. Within these applications, DOE could promote cool pavements through pilot projects and model codes.

Policy Opportunities

Numbered headings indicate report location containing supporting information
* *items are highlighted in the Executive Summary*

International

4.1.4.d. Expansion of the scope of the Global Methane Initiative

4.2.4.b. Amendment of the Montreal Protocol to include N_2O (*)

4.2.4.c. International cooperation on N_2O emissions reductions under the Major Economies Forum or the Global Research Alliance on Agricultural Greenhouse Gases

4.2.4.f. Creation of an offset protocol for N_2O emissions from nitric acid production

4.3.4.b. International cooperation to address black carbon emissions from brick kilns

4.3.4.c. International cooperation to reduce black carbon emissions that reach "hot spots"

4.3.4.d. International collaboration to share diesel fuel technologies with developing countries

4.3.4.e. Creation of an annual international meeting on black carbon

4.3.4.h. Addition of black carbon mitigation to the list of potential GEF projects

4.4.4.b. Establishment of financial support for ODS bank removal projects in developing countries

4.6.4.a. International cooperation to identify financing mechanisms for aluminum smelter retrofits in developing countries (*)

4.6.4.b. International cooperation to reduce PFC emissions from electronics and semiconductor manufacturing (*)

4.6.4.c. Establishment of ambitious domestic and international aluminum recycling goals

4.6.4.d. Development of international standards for anode effects during aluminum production

4.7.4.c. International engagement to promote alternative cover gases in magnesium production

4.8.4.a. International collaboration on NF_3 emissions reductions in a task force on non-CO_2 climate forcers

4.9.4.f. Inclusion of cool pavements in the work plan for the Global Superior Energy Performance Partnership

5.1.b. Creation of a task force on non-CO_2 climate forcers in an appropriate international forum (*)

Domestic

4.1.4.a. EPA regulation of methane emissions (*)

4.1.4.b. Financial incentives for landfill and coal mine gas electricity generation

4.1.4.c. State facilitation of grid connection of landfill and coal mine gas

4.1.4.e. Model waste management policy design

4.1.4.f. Support for campaigns to reduce meat consumption in government cafeterias

4.2.4.a. Establishment of N_2O performance standards under the Clean Air Act (*)

4.2.4.d. Expansion of light-duty vehicle N_2O cap to all vehicle classes

4.2.4.e. Identification and development of methodologies for the measurement of agricultural N_2O emissions

4.3.4.a. Policy support for installation of diesel particulate filters in heavy-duty vehicles

4.3.4.f. Tightening of vehicle efficiency standards to mitigate black carbon emissions

4.3.4.g. Expansion of funding for retrofit programs through loan guarantees for retrofits by small fleet operators and farms

4.4.4.a. DOE expansion and modification of Cash for Appliances program (*)

4.5.4.a. EPA withdrawal of SNAP approval of HFC-134a (*)

4.5.4.b. EPA and NHTSA incorporation of low-GWP refrigerant credits for medium-duty, heavy-duty, and off-highway vehicle classes (*)

4.5.4.c. Engagement with large commercial cooling and retail food refrigeration industries to reduce HFC leakage in existing and new equipment (*)

4.5.4.d. Establishment of voluntary GWP standards for refrigerants under the EPA Greenchill partnership

4.5.4.e. Climate impact labeling

4.5.4.f. Mandatory certification for HFC sales and service

4.5.4.g. Mandatory HFC-23 destruction

4.5.4.h. Implementation of a cap on HCFCs and HFCs through amendment of the Clean Air Act

4.5.4.i. DOE support for research and development of HFC alternatives

4.6.4.c. Establishment of ambitious domestic and international aluminum recycling goals

4.7.4.a. Agency administration of SF_6 recycling programs and required leak detection and repair programs in the electric power system sector

4.7.4.b. Partnership with industry to support efforts to reduce SF_6 emissions from semiconductor and thin film manufacturing

4.8.4.b. EPA expansion of NF_3 emissions reporting requirement to all sectors

4.8.4.c. Establishment of sectoral caps on NF_3 emissions

4.9.4.a. Analysis of the potential scale of cost-effective cool roof deployment through federally funded building construction and roof repairs

4.9.4.b. Promotion of high-albedo paving material use in applications with an unambiguous climate benefit (*)

4.9.4.c. Support for adoption of model building codes by state and local governments

4.9.4.d. Analysis of cool roof programs as a demand reduction strategy to avoid the need for new power plants

4.9.4.e. Addition of cool roofs to the criteria for ranking of state and municipality grant applications for federal funds

4.9.4.g. Establishment of DOE authority to regulate roofing via new rulemaking or new legislation

4.9.4.h. Establishment of enhanced financial incentives for cool roof investments

4.9.4.i. Diversification of research institutions funded to research cool roofs and pavements

5.1.a. Consideration of life cycle emissions (*)

R&D

4.1.4.g. Agricultural methane emissions reductions research

4.5.4.i. DOE support for research and development of HFC alternatives

4.6.4.b. Research and development on cost-effective technologies to reduce PFC emissions from electronics and semiconductor manufacturing (*)

4.9.4.d. Analysis of cool roof programs as a demand reduction strategy to avoid the need for new power plants

4.9.4.i. Diversification of research institutions funded to research cool roofs and pavements

4.9.4.j. Research on potential value of cool roof and cool pavement projects in future carbon markets

I. Introduction

International and domestic efforts have thus far failed to put in place the policies necessary to significantly reduce the risk of dangerous anthropogenic interference in the climate system. Mitigation discussions have, to date, focused on options for reducing carbon dioxide (CO_2) emissions because CO_2 is responsible for the greatest amount of global warming and controls the long-term evolution of Earth's temperature.

However, non-CO_2 climate forcers are responsible for almost half of the planet's total positive human-caused radiative forcing, and it will be necessary to employ fast action strategies to address these forcers if we are to slow the acceleration of global warming in the next decade. Under a best-case scenario, current international pledges to reduce greenhouse gas emissions under the Copenhagen Accord would only account for 60 percent of necessary emissions reductions by 2020. Roughly translated, that means that up to 40 percent of action on climate change may need to come from the fast-action non-CO_2 strategies that are the focus of this report (UNEP, 2010a). It will not be possible to fully address the challenge of anthropogenic climate change without addressing non-CO_2 climate forcers.

We define "climate forcer" as any gas, particle, or effect that contributes to climate change. While most non-CO_2 climate forcers have significantly lower emission rates than CO_2, many have much higher global warming potentials (GWPs) and high projected emissions growth rates. Strategies to reduce emissions of non-CO_2 forcers present potentially significant opportunities to slow the rate of global warming.

While reducing CO_2 emissions must be the top priority of climate change policies, avoiding potentially catastrophic climate change will require a multifaceted approach. From the perspective of the United States, this report surveys both domestic and international opportunities to mitigate non-CO_2 forcers, focusing on fast-action strategies that are available under current authority. Fast-action strategies are defined as those which can begin in two to three years, be substantially implemented within five to ten years, and have the goal of producing the desired climate response within decades (Molina et al., 2009).

This report recommends policies that could be implemented by the United States government under current authority, focusing on policies that could be implemented by the United States Environmental Protection Agency (EPA), the United States Department of Energy (DOE), or their interagency partners.

We consider strategies addressing three main categories of climate forcers:

- Reducing emissions of non-CO_2 greenhouse gases (GHGs), including methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and emissions from ozone-depleting substance (ODS) banks;
- Making targeted reductions in the emissions of black carbon that maximize net climate benefits; and
- Reducing radiative forcing by increasing the reflectivity and emissivity of roofs and pavements.

From these options, we select a subset of top policy opportunities based on the following criteria:

1. potential impact on the climate, including consideration of emissions growth rates,
2. speed of implementation,
3. maturity of technology,
4. cost to government,
5. cost to private sector, and
6. co-benefits.

This report represents the synthesis of policy and academic literature reviews; interviews with academic researchers, subject matter experts, policymakers, and private sector stakeholders; and original analysis.

II. Science and Metrics

Earth's energy balance is a delicate equilibrium maintained by incoming solar radiation and outgoing terrestrial radiation. This balance can be disrupted by adding gases or particles to the atmosphere that absorb or scatter radiation, thereby either trapping more energy in the climate system or reflecting more energy out to space. As humans continuously emit more substances into the atmosphere, the energy balance shifts accordingly, causing climate change.

In order to determine a forcing agent's contribution to global warming, a variety of metrics are used to quantify its impact. There is debate as to which metrics are most appropriate for describing the climate impact of the multitude of forcing agents affecting earth's energy balance. This report utilizes three common metrics: radiative forcing, global warming potential (GWP), and CO_2 equivalent emissions (CO_2eq), as tools to quantify and compare the climatic impacts of non-CO_2 climate forcing agents. These metrics are compared in Table 2.1.

Metric	Definition	Advantages	Limitations
RADIATIVE FORCING (W/m^2)	Physical measure of the amount of energy trapped (positive value) in the atmosphere by a climate forcing agent	Can be used for all climate forcers: • Greenhouse gases • Short-lived particles • Albedo changes	Instantaneous measurement; the lifetime of the forcer is not considered
GLOBAL WARMING POTENTIAL (GWP)	Derived scalar used to describe the warming potential of a gas relative to CO_2 over a specified period of time; typically measured in 20-year (GWP_{20}) or 100-year (GWP_{100}) periods	Incorporates the atmospheric lifetime of a gas; captures long-term climate impact; allows for comparison of impacts across different climate forcers	Best used for well-mixed and long-lived gases; deciding which timeframe to use (GWP_{20} or GWP_{100}) can result in different projections regarding the scale of impact a gas will have on the climate system
CARBON DIOXIDE EQUIVALENT (metric ton CO_2eq)	Amount of CO_2 that would have the same GWP as climate forcer	Standardizes the projected impact from climate forcers in terms of CO_2 equivalent mass	Same as GWP

Table 2.1: The relative contribution of each climate forcer to warming of the climate system using three different metrics. The first identifies the contribution to total radiative forcing, based on the amount of each agent that is currently in the atmosphere. The second and third charts represent the contribution of current annual emissions of each agent to warming in terms of equivalent carbon dioxide, that is, the amount of CO_2 that would exert the same radiative forcing over a specified period of time, over 20 years for GWP_{20} and over 100 years for GWP_{100}.

Another way to think about how these three metrics relate to one another is the following: The radiative forcing of a forcing agent is intrinsic to that forcer (depending on factors such as its molecular structure and atmospheric concentration), the GWP of GHG X is the integrated radiative forcing over a set period of time (often 100 years) and this GWP can be described in terms of CO_2 equivalent emissions by multiplying the emissions of X by the GWP of X. For example, if CH_4 has a GWP_{100} of 25, and its annual emissions are 280 million metric tons, this forcer has CO_2eq annual emissions of 25 x 280 million metric tons. Thus, CO_2eq is a necessary metric for comparing the emissions of different GHGs, which have different GWPs, in a uniform manner.

The relative contribution of each climate forcer addressed in this report to global warming is presented in Figure 2.1 using each of these three metrics.

As can be seen in Figure 2.1, non-CO_2 climate forcers currently comprise slightly less than one-half of the total radiative forcing in the atmosphere. Of these non-CO_2 forcers, methane and black carbon exert the strongest forcing. Although using different metrics appears to change the scale of importance of non-CO_2 climate forcers to that of CO_2, the relative importance of each individual non-CO_2 forcer remains steady within a given metric framework.

Due to the high variability in atmospheric lifetime of climate forcers, GWP_{100} is often used in cross-comparing their effect. Whereas GWP_{100} captures the total climate impact of short-lived forcers, GWP_{100} does not capture the full climate impact of forcers that have longer lifetimes than the GWP timescale. GWP_{100} also scales down the impact of forcers with shorter lifetimes, allowing short-lived forcers to appear less important. Therefore, if we care about temperature changes in the next few decades, using a metric with a long timescale skews and downplays the importance of several significant climate forcers in the near-term.

For example, the average lifetime of the HFCs in use today is 21.7 years, better suited to GWP_{20}. By using GWP_{100} as the main measure of their potency, their impact is being averaged over a much longer timescale than they are actually in the atmosphere. Nevertheless, this report uses GWP_{100} in order to compare climate impacts and cost estimates among mitigation potentials for the purpose of consistency with previous literature, keeping in mind the limitations of this metric discussed above.

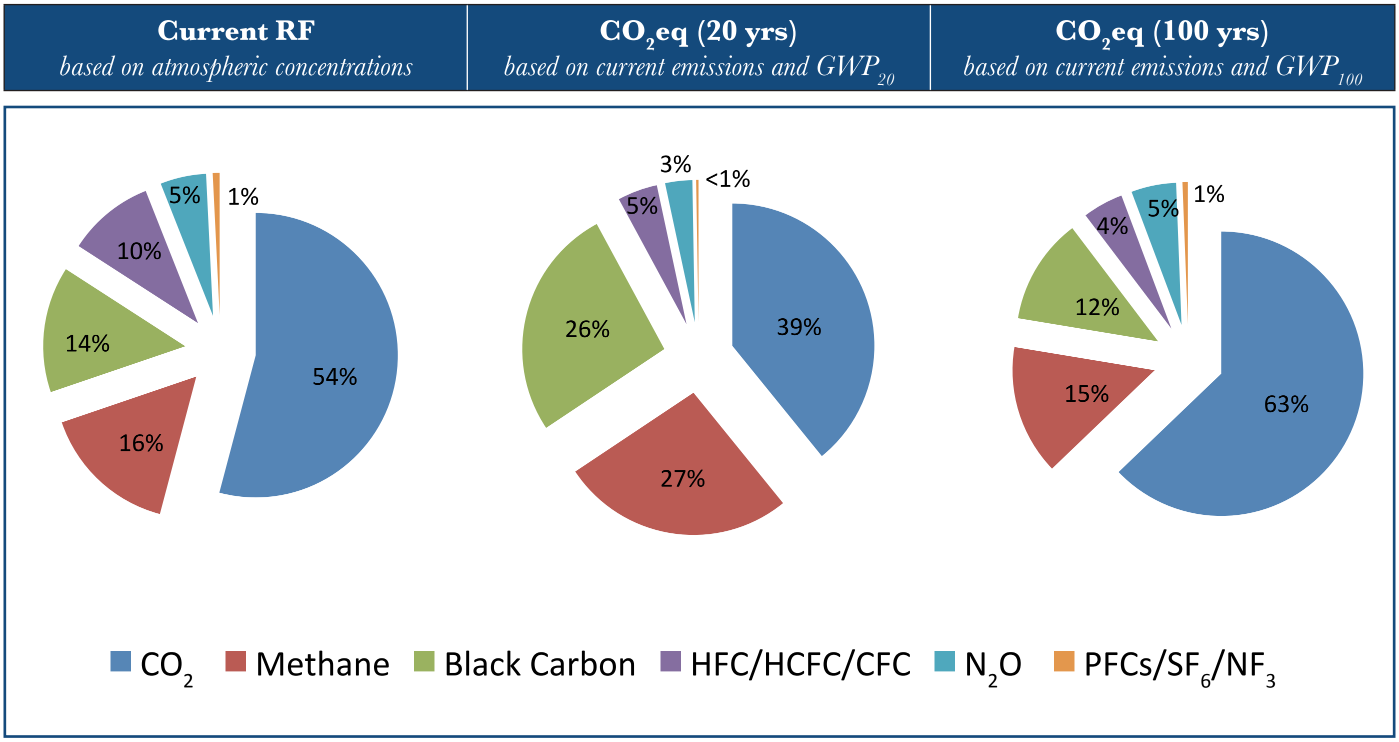

Figure 2.1: The relative contribution of each climate forcer to warming of the climate system using three different metrics. The first column identifies contribution to total radiative forcing, based on the amount of each agent that is currently in the atmosphere. The second and third columns represent the contribution of current emissions of each agent to warming in terms of equivalent carbon dioxide, that is, the amount of CO_2 that would exert the same radiative forcing over a specified period of time. Approximate current emissions per year were used to calculate the CO_2eq.

To give an example of how using different metrics and timeframes may impact recommended mitigation strategies, Table 2.2 compares the magnitude of mitigation needed for each of the non-CO_2 climate forcers addressed in this study to mitigate the equivalent annual emissions of a 500 MWe coal power plant (3 $MtCO_2$ per year). The integrated radiative forcing over 100 years (GWP_{100}) and over 20 years (GWP_{20}) for an emission pulse of 3 $MtCO_2eq$ are included in the first and second columns respectively, while the radiative forcing for the same pulse is included in the third column. From this chart it can be seen that the yearly emissions from one 500 MWe coal plant has the same 100-year forcing as 12 percent of U.S. PFC emissions, 750 percent of U.S. NF_3 emissions, and 0.6 percent of U.S. methane emissions. Due to the short-lived nature of black carbon in the atmosphere, mitigating the equivalent (GWP_{100}) yearly emissions of a 500 MWe coal power plant would require the retirement or retrofit of 15,000 pre-regulation heavy-duty diesel trucks (assuming a ten year anticipated remaining vehicle life). However, if the equivalent radiative forcing from a pulse of 3 $MtCO_2$ is used to estimate an equivalent emissions reduction, only 10 pre-regulation vehicles would need to be retired or retrofitted. This means that at any given point in time the warming contribution from 100 pre-regulation vehicles is as great as a whole power plant.[1] This last point illustrates the importance of understanding which metric is being used in determining climate effects.

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[1] The power plant emission pulse is based off of one year, while the emission reduction from the vehicles is based off of a ten year lifetime. Thus for an any-point-in-time comparison, the vehicle number was multiplied by ten to equate it with the emissions from one year.

ANNUAL (based on 2005 emission levels)			
Forcer	**GWP_{100} Mitigation Options**	**GWP_{20} Mitigation Options**	**RF Mitigation Options**
CO_2	Remove one 500 MWe coal power plant (only accounting for CO_2 emissions)		
Methane (CH_4)	Reduce U.S. methane emissions by 0.6%, i.e. capture 2% of U.S. landfill emissions	Reduce U.S. methane emissions by 0.6%	Reduce U.S. methane emissions by 0.6%
N_2O	Reduce U.S. N_2O emissions by 0.8%, or upgrade 4% of nitric acid plants worldwide to best available technology	Reduce U.S. N_2O emissions by 0.8%	Reduce U.S. N_2O emissions by 1.4%
Black Carbon	Reduce U.S. black carbon emissions by 0.7%, i.e. take 15,000 pre-regulation heavy duty vehicles off the road, or adopt 750,000 clean wood cookstoves	Take 4,500 pre-regulation heavy duty vehicles off the road, or adopt 210,000 clean wood cookstoves (0.2% of Global Alliance for Clean Cookstoves goal)	Take 10 pre-regulation heavy duty vehicles off the road, or adopt 500 clean wood cookstoves
CFC/HCFC/HFC	Reduce U.S. HFC emissions by 2.3%, or dispose of 2.7 million refrigerators (3.6% of worldwide decommissioning)	Dispose of 2.7 million refrigerators (3.6% of worldwide decommissioning)	Dispose of 3.6 million refrigerators (5% of worldwide decommissioning)
PFC	Reduce U.S. PFC emissions by 11.8%, i.e. bring 5% of median performing aluminum plants to best practice	Reduce U.S. PFC emissions by 17.3%	Reduce U.S. PFC emissions by 27.7%
SF_6	Reduce U.S. SF_6 emissions by 15.6%, or recycle 4% of SF_6 possible used in electric grids worldwide	Reduce U.S. SF_6 emissions by 21.1%	Reduce U.S. SF_6 emissions by 30.5%
NF_3	Reduce worldwide NF_3 emissions by 30%, or reduce U.S. NF_3 emissions from semiconductor manufacturing by 750%	Reduce worldwide NF_3 emissions by 40%	Reduce worldwide NF_3 emissions by 41%
Roofs and Pavements	Increase albedo by 0.15 on 70 km^2, i.e. 40% of the area of Washington, D.C.	Increase albedo by 0.15 of 98 km^2	Increase albedo by 0.15 of 144 km^2

Table 2.2: Metric Comparison of Equivalent Forcings. The reductions needed by each climate forcer to be equivalent to the CO_2 emissions from one 500 MWe coal power plant is shown. These numbers are based on 2005 yearly emissions, with the exception of black carbon, which is based on the instantaneous amount in the atmosphere due to its lifetime being much less than one year.

III. Existing Literature on Abatement Potential and Costs

This report draws primarily from cost and benefit estimates from two sources: EPA's 2006 report *Global Mitigation of Non-CO_2 Greenhouse Gases* (EPA, 2006a) and a forthcoming report by McKinsey & Company on abatement technologies and costs for non-CO_2 climate forcers (McKinsey, 2010).

Both reports compare abatement costs and potentials for a range of technologies to reduce emissions of non-CO_2 climate forcers. The EPA report estimates costs and technical potential for reducing emissions of non-CO_2 greenhouse gases (CH_4, N_2O, HFCs, CFCs, and SF_6). The McKinsey report builds on EPA's analysis and adds analysis for black carbon.

Both reports cite significant potential for mitigating non-CO_2 climate forcers at negative to zero net cost. According to EPA's report, the worldwide potential for reducing yearly emissions of non-CO_2 greenhouse gases at negative or zero cost is greater than 600 MtCO_2eq in 2020, or roughly 2 percent of global CO_2 emissions in 2007 (IEA, 2010). EPA reports over 2,000 million metric tons CO_2eq (MtCO_2eq) of mitigation potential, equivalent to the combined annual CO_2 emissions of India and Indonesia, available at net costs below $10 per metric ton CO_2eq (tCO_2eq). EPA reports that an additional 700 MtCO_2eq of mitigation can be realized at costs below $60 per t$CO_2$eq.

McKinsey's report also cites significant potential for reducing the emissions of non-CO_2 climate forcers. McKinsey estimates that about 2,300 MtCO_2eq of emissions could be avoided at negative or zero cost in 2030.

The reliability of the cost estimates reported by EPA and McKinsey is limited by uncertainty in the underlying assumptions. Several experts interviewed during the preparation of this report expressed skepticism in these estimates of abatement cost and potential, with some citing specific examples of estimates that are outdated or inaccurate. It is also worth noting that these studies explicitly do not provide detail on (1) policies that could enable adoption of the mitigation options, (2) transaction costs, or (3) the distribution of abatement costs and cost savings. Nevertheless, these studies remain the best available comprehensive assessments of abatement costs and potential.

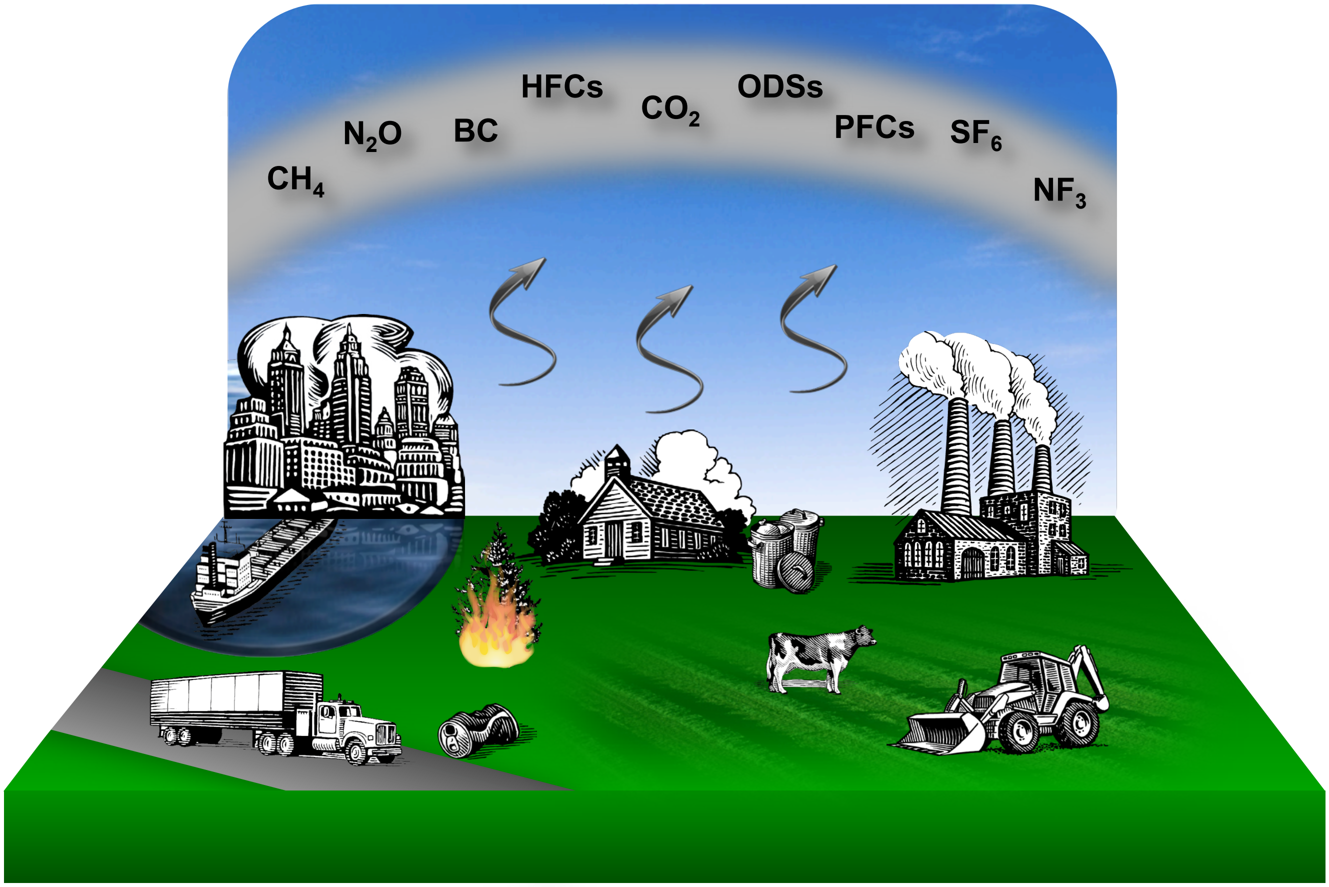
IV. Survey of Non-CO_2 Climate Forcers and Policy Opportunities

Non-CO_2 forcers are a collectively significant set of climate changing agents with a diverse array of emission sources, impacts, and current policy landscapes. In this section, we outline these factors for each climate forcer and identify policy opportunities for climate impact mitigation, focusing on (1) fast-action strategies, (2) strategies that could be implemented by EPA or DOE, and (3) strategies possible under current agency authority. The policy opportunities are general both in terms of technical and administrative implementation. The set of policy opportunities is not intended to be comprehensive, but instead aims to reflect the range of potential mitigation policies.

A subset of the policy opportunities we identified were selected as top policy opportunities. These policy opportunities are denoted **(*)** and are presented in greater detail in Section 5.

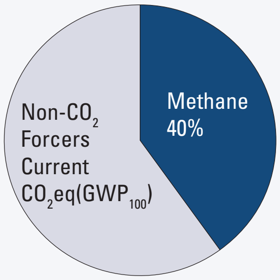
Climate forcers are presented in the following order:

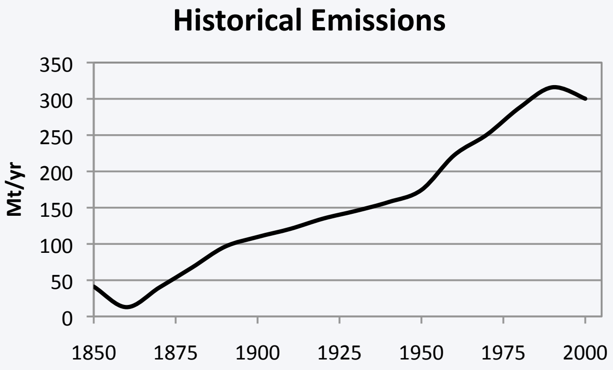
1. Methane (CH_4)
2. Nitrous oxide (N_2O)
3. Black carbon
4. Hydrofluorocarbons (HFCs)
5. Ozone depleting substance (ODS) banks
6. Perfluorocarbons (PFCs: CF_4, C_2F_6, and C_3F_8)
7. Sulfur hexafluoride (SF_6)
8. Nitrogen trifluoride (NF_3)
9. Roof and pavement reflective and emissive properties

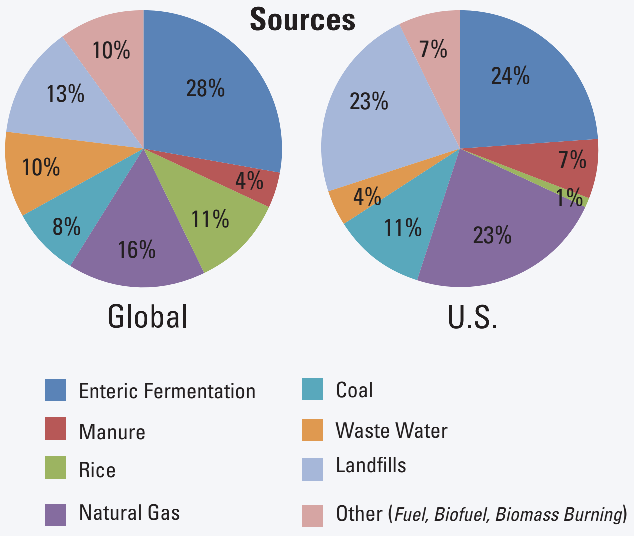


4.1. METHANE (CH_4)

GWP_{20} = 72
GWP_{100} = 25
Atmospheric Lifetime = 12 years







References:
GWPs & lifetime – IPCC, 2007
Historical emissions – RCP Database, 2009
Global sources – EPA, 2006
U.S. sources – EPA, 2009

4.1.1. Emission sources

Agricultural emissions account for over half of human-related global methane (CH_4) emissions. Methane emissions are also associated with fossil fuel production and distribution and with organic waste decomposition.

Emissions from livestock management, specifically emissions from enteric fermentation, are the largest source of human-related methane emissions globally. Enteric fermentation accounts for 30 percent of total human-related methane emissions. Methane production in flooded rice paddies via anaerobic decomposition of soil organic material comprises 11 percent of total methane emissions.

Approximately 25 percent of global human-related methane emissions are associated with fossil fuel production and distribution. Methane is emitted during natural gas production and distribution because methane is the primary component of natural gas. Methane can leak from valves, pumps, and pipelines within production and distribution systems.

Methane is also emitted during the production of coal and oil because methane is present in the coal beds and oil deposits and can be released during extraction. Methane is vented during coal production due to mining safety procedures. Methane emissions from coal mining are expected to rise because of projected increases in coal mining to meet global demand for coal. It is technologically feasible to capture much of the methane associated with both coal and oil production. However, the decision of whether to recover methane during coal or oil production depends on economic factors which tend to be more favorable for oil production due to high concentrations and pressures. However, smaller remote oil platforms with no access to natural gas pipelines may choose to vent the gas into the atmosphere.

About 19 percent of global human-related methane emissions result from the anaerobic digestion of organic components of waste (EPA, 2006b). Landfill emissions comprise nearly 50 percent of waste methane emissions, while wastewater emissions comprise close to 40 percent. Methane emissions from landfills can be avoided by capturing or flaring methane. Estimates of global waste methane emissions may be revised in the near future, because the Intergovernmental Panel on Climate Change (IPCC) is currently revising the metrics for measuring methane emissions from landfills in developing countries.

4.1.2. Impacts of emissions

Methane emissions exert a strong influence on the climate. Methane has a GWP_{100} of 25 and an atmospheric lifetime of 12 years. Methane accounts for 14 percent of the current radiative forcing from greenhouse gases in the atmosphere and comprises 63 percent of annual CO_2eq (GWP_{100}) emissions of non-CO_2 greenhouse gases.

Methane emissions also have human health, ecosystem, and agricultural impacts because methane is a precursor for tropospheric ozone formation. Exposure to elevated ozone concentrations is associated with human health risks, ecosystem damage, and decreased agricultural yields. A 65 $MtCO_2eq$ (GWP_{100}) annual reduction in methane emissions is estimated to potentially prevent approximately 30,000 premature mortalities in 2030 and approximately 370,000 between 2010 and 2030 (West et al., 2006).

4.1.3. Current policies and policies under development

Current domestic policies for reducing methane emissions have focused on (1) providing subsidies for electricity generation fueled by methane captured from coal mines and landfills, and (2) fostering technology transfer and capacity building. A number of state renewable portfolio standards count power generated from methane from waste as alternative energy. Pennsylvania, Ohio, West Virginia and Utah all award utilities alternative energy credits for power generated from coal mine methane. EPA regulations mandate gas recovery for a small fraction of solid waste landfills that are above a certain size. The federal government also assists projects that put methane from landfills and coal mines to beneficial use through grants, tax credits, and subsidized loan programs. DOE is considering implementing a methodology proposed by the National Academy of Sciences to use full-fuel-cycle accounting for measuring energy efficiency savings.

The Global Methane Initiative is an EPA-sponsored voluntary program that focuses on advancing cost-effective technologies to reduce methane emissions from agriculture, natural gas production and transportation, coal mining and waste. Partner companies are expected to take advantage of the mitigation opportunities supported by the partnership and submit annual reports on progress made towards reducing methane emissions. The partnership has assisted 170 projects globally so far which reduced annual methane emissions by 26.7 $MtCO_2eq$ in 2008 (EPA, 2009a). Through this initiative, EPA also supports technology transfer to and capacity building in developing countries.

The Supreme Court decision in 2007 that designated CO_2 and other greenhouse gases as air pollutants gave EPA authority to regulate methane emissions under the Clean Air Act. Under Section 111 of the Clean Air Act, state environmental agencies can require best available pollution control technologies on new and existing plants, which could now include control systems for greenhouse gas mitigation. EPA will require all industrial facilities with emissions greater than 25,000 tCO_2eq to report emissions by March 2011.

Under various directives, European Union countries have committed to (1) mandatory reduction biodegradable waste streams into landfills according to mandatory targets (25, 50 and 65 percent below 1995 land-fill waste stream levels in 2006, 2009 and 2016 respectively) and (2) mandatory gas recovery from all landfill sites under the Landfill Directive, the Waste Directive, and the Waste Management Framework Directive. These commitments are nuanced with waste stream diversion hierarchies and grace periods for counties with heavy reliance on solid waste landfills (Hoglund-Isaksson et al., 2010).

Methane is one of the six greenhouse gases controlled under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 1997).

4.1.4. Near-term policy opportunities

4.1.4.a. EPA regulation of methane emissions (*) – Under the Clean Air Act, EPA could mandate the reduction or beneficial use of methane emissions from new stationary sources and certain existing facilities. For landfills and coal mines, regulation could encourage the beneficial use of methane and reduce incentives for gas flaring.

4.1.4.b. Financial incentives for landfill and coal mine gas electricity generation – Feed-in-tariffs, taxes and/or subsidies could be employed to stimulate the substitution of landfill and coal mine natural gas electricity generation for more carbon intensive fossil fuel generation.

4.1.4.c. State facilitation of grid connection of landfill and coal mine gas – States could follow Massachusetts' example and accelerate the grid connection of coal mine methane and landfill-to-energy projects. Massachusetts reduced regulatory uncertainty for landfill-to-energy projects through streamlined interconnection policies. EPA and DOE could provide guidelines to states to implement these policies.

4.1.4.d. Expansion of the scope of the Global Methane Initiative – Member governments of the Global Methane Initiative are expected to develop plans to mitigate domestic methane emissions. To support these efforts, EPA could facilitate the sharing of best practice policies. The U.S. has been a leader in voluntary efforts to reduce methane emissions and could build on this credibility to support international efforts to regulate methane emissions. The U.S. could assist countries in designing and implementing policies to reduce methane emissions even in sectors that have traditionally been more important abroad—for example, providing technical and financial support to Asian countries to facilitate reductions in methane emissions from rice paddy management.

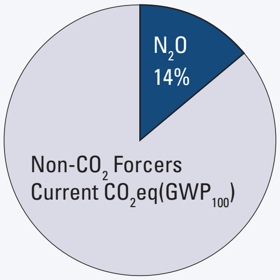
4.1.4.e. Model waste management policy design – EPA could design model policies for recycling, composting and anaerobic digestion.

4.1.4.f. Support for campaigns to reduce meat consumption in government cafeterias – The Food and Agriculture Organization of the United Nations reports that meat has a higher energy intensity and greater climate impacts than other foods (Steinfeld et al., 2006). Agencies could support "Healthy Mondays" or "Meatless Mondays" campaigns in government-run cafeterias to offer vegetarian food one day a week (Healthy Mondays, 2010). Efforts to encourage moderation in meat consumption can reduce methane and CO_2 emissions and yield cost savings.

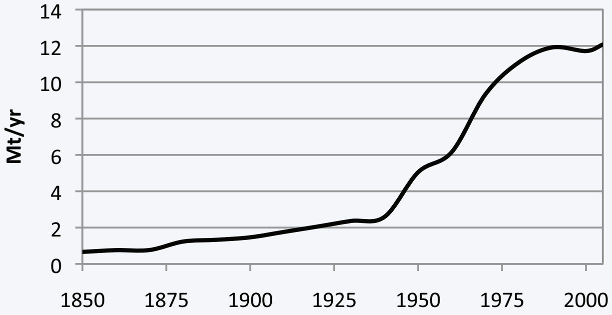
4.1.4.g. Agricultural methane emissions reductions research – The ability to formulate policy to promote short-term methane emissions mitigation strategies for much of the agricultural sector is hampered by uncertainty in projections of the net effects of intervention. For instance, several technologies exist that can reduce methane emissions per livestock animal, including hormones, feed changes, and vaccines. However, projections of the net effect of most mitigation technologies in the agricultural sector are uncertain (EPA, 2006a). Additional research on the system-wide effects of many agricultural methane emissions mitigation technologies will enable future reductions.

4.2. NITROUS OXIDE (N_2O)

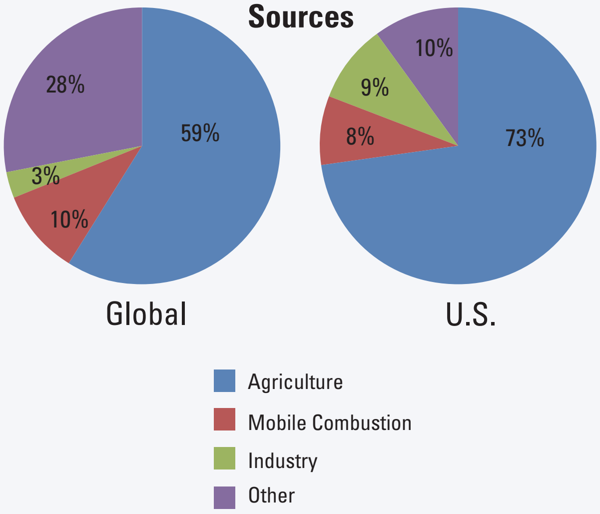
GWP_{20} = 289
GWP_{100} = 298
Atmospheric Lifetime = 114 years



Historical Emissions



Sources



References:
GWPs – IPCC, 2007
Atmospheric Lifetime – IPCC, 2007
Historical emissions – RCP Database, 2009
Global sources – EPA, 2006
U.S. sources – U.S. Climate Action Report, 2010

4.2.1. Emission sources

The majority of anthropogenic nitrous oxide (N_2O) emissions are associated with agriculture, waste management, fossil fuel combustion, and industrial processes.

Nearly 60 percent of global N_2O emissions are associated with agriculture. Almost half of agricultural N_2O emissions originate from livestock manure management. The remaining agricultural N_2O emissions are from synthetic fertilizer use (27 percent), nitrogen-fixation (16 percent), and crop residues (9 percent) (Crutzen et al., 2010). N_2O is also emitted from waste when nitrogen-bearing organic compounds are broken down.

N_2O is a component of vehicle exhaust due to reactions between nitrogen and oxygen. Catalytic converters, which were introduced to reduce nitrogen oxide (NO_x) emissions under the Clean Air Act, can actually increase N_2O production in exhaust. Technical modifications to converters are addressing this problem (EPA, 2006a).

Three percent of global N_2O emissions are associated with industrial activity. N_2O emissions from the production of nitric acid, a precursor in the manufacture of fertilizer and explosives, account for 65 percent of global industrial N_2O emissions (EPA, 2006a). In this process, N_2O is formed as a by-product of the oxidation of ammonia (Wiesen, 2010). The N_2O produced per unit of nitric acid produced varies widely with manufacturing plant age, type, and operating conditions. N_2O emissions from nitric acid production are expected to increase by 13 percent during the period 2000-2020 because the market for synthetic fertilizer is expanding.

N_2O emissions from the production of adipic acid, a compound used primarily as the main constituent of nylon, account for 35 percent of global industrial N_2O emissions. Global N_2O emissions from adipic acid production are projected to increase by approximately 40 percent between 2000 and 2020 due to increased demand for nylon (EPA, 2006a). However, U.S. N_2O emissions from adipic acid production have decreased substantially since 1996 and are expected to continue to decrease. This is due to the installation by nearly all adipic acid producers of NO_x abatement technologies in response to EPA ground level ozone reduction programs, which also reduce N_2O emissions by at least 90 percent (Wiesen, 2010).

4.2.2. Impacts of emissions

N_2O emissions exert a strong influence on the climate. N_2O has a GWP_{100} of 298 and an atmospheric lifetime of 114 years. N_2O accounts for 10 percent of the current radiative forcing from greenhouse gases in the atmosphere and comprises 14 percent of annual CO_2eq (GWP_{100}) emissions of non-CO_2 greenhouse gases.

4.2.3. Current policies and policies under development

In May 2010, EPA and the Department of Transportation set a cap on tailpipe emissions of N_2O of 0.010g per mile. N_2O accounts for less than one percent of overall vehicle greenhouse gas emissions from new vehicles. Accordingly, the goal of this standard is "to limit any potential increases of tailpipe emissions of these compounds in the future but not to force reductions relative to today's low levels" (EPA and DOT, 2010).

As of October 2010, EPA requires nitric acid and adipic acid producers to report on N_2O emissions and abatement technologies employed (EPA, 2010b).

The province of Alberta, Canada has implemented a protocol that generates carbon offsets from the reduction of N_2O emissions in nitric acid plants (Alberta Environment, 2009). The Alberta Offset System allows large industrial emitters who need to comply with the province's greenhouse gas emissions reduction program to purchase offset credits from other sectors that have voluntarily reduced their emissions in Alberta.

Credits for N_2O abatement from nitric acid plants will be available under the EU Emissions Trading Scheme beginning in 2013, under Directive 2009/29/EC. While a 2009 EC Directive would have allowed credits from N_2O reduction from adipic acid plants to be used in the EU Emissions Trading Scheme, the European Commission released a draft regulation in November 2010 that would prohibit the use of international credits gained by such means. However, although an EU country could not buy foreign credits for N_2O reductions from adipic acid plants, credits for reductions from nitric acid plants would be allowed. They explain that the credits issued for such projects flood the carbon market and "do not contribute to technology transfer or to the necessary long-term transformation of energy systems in developing countries" (EC, 2010).

N_2O is one of the six greenhouse gases controlled under the UNFCCC Kyoto Protocol (UNFCCC, 1997).

4.2.4. Policy opportunities

4.2.4.a. Establishment of N_2O performance standards under the Clean Air Act (*) – N_2O is an ozone depleting substance with an ozone depletion potential (ODP) of 0.017, which is below the 0.2 threshold necessary for its mandatory inclusion as a class I substance for regulation under the Clean Air Act. However, N_2O could be listed as a Class II substance at the discretion of the EPA Administrator or regulated under Section 615 of the act. This would provide EPA with the opportunity to regulate N_2O without waiting for new climate legislation that includes N_2O. An industrial standard could be based on the N_2O emissions rates from the best performing nitric and adipic acid plants. This would emulate the EU "average best 10 percent" policy for N_2O emissions from nitric acid plants. This policy may require expanded agency authority.

4.2.4.b. Amendment of the Montreal Protocol to include N_2O (*) – The Montreal Protocol is considered one of the most successful environmental treaties to date, with the additional benefit of all the Parties (both developed and developing countries) having legally binding obligations. The Protocol has the legal authority to control N_2O, given its ozone depleting properties and has already acted explicitly to deliver a climate co-benefit by accelerating the phase-out of HCFCs in 2007. Moreover, its success is to a large part due to U.S. leadership, so controlling N_2O under the Montreal Protocol could offer the U.S. an opportunity to underscore its commitment to international climate policy.

4.2.4.c. International cooperation on N_2O emissions reductions under the Major Economies Forum or the Global Research Alliance on Agricultural Greenhouse Gas Emissions – International cooperation on N_2O emissions could foster a discussion on global standards and technology-sharing pathways for N_2O abatement technologies from nitric acid plants. In addition, it could play an important role in establishing transnational research efforts to monitor and reduce N_2O emissions from agricultural sources.

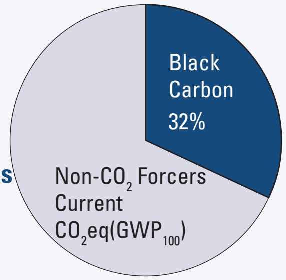
4.2.4.d. Expansion of light-duty vehicle N_2O cap to all vehicle classes – Work is underway in the transportation sector to reduce N_2O emissions. Mobile combustion was responsible for 8 percent of N_2O emissions reported in 2008, a decrease from 15 percent in 2000. One N_2O emission reduction initiative, proposed by EPA and the Department of Transportation, is to cap tailpipe N_2O emissions at 0.010 grams per mile. This is part of a wider effort to reduce greenhouse gas emissions and improve fuel economy for light-duty vehicles. These efforts could be expanded to include all vehicle classes, which would cover the 50 percent of N_2O emissions from mobile sources not currently regulated (EPA, 2010c).

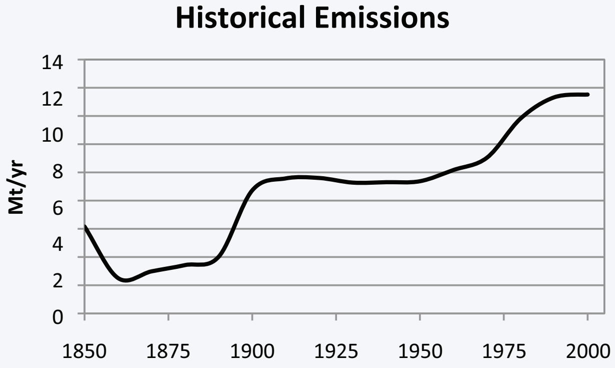
4.2.4.e. Identification and development of methodologies for the measurement of agricultural N_2O emissions – We have not identified specific policy opportunities for mitigating agricultural emissions because of the current difficulty in identifying low-cost simple direct N_2O measurement methodology for this sector. Reporting of N_2O emissions from agricultural soil management was not included in the Final Mandatory Reporting of Greenhouse Gases Rule issued by EPA on September 22, 2009 for this reason. EPA has allocated financial resources to quantify N_2O emissions for the greenhouse gas inventory, but feasible measurement methodologies must be developed before EPA or the Department of Agriculture can commence reporting N_2O emissions from agricultural sources.

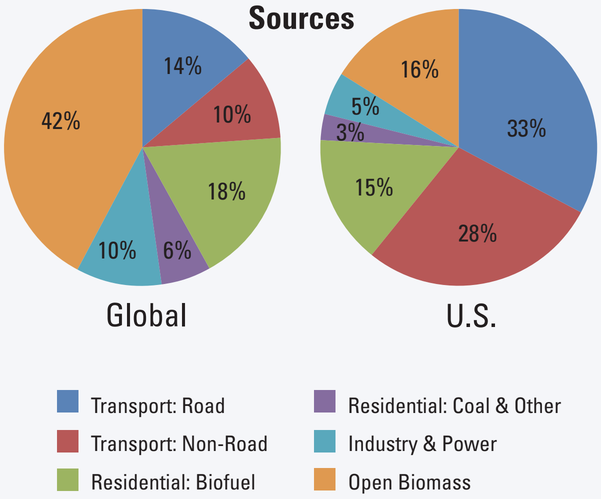
4.2.4.f. Creation of an offset protocol for N_2O emissions from nitric acid production –The EU Emissions Trading Scheme will cover N_2O emissions from nitric acid plants starting in 2013. However, given that the U.S. does not have a national carbon market, it would be more feasible to follow the initiative of the province of Alberta, Canada, and create a federal trading scheme for N_2O emissions from nitric acid plants. Such a protocol could apply the same approach as the federal trading scheme that reduced acid rain, given the sector-specific nature of N_2O emissions from nitric acid plants. It could also improve on the current practice of the Clean Development Mechanism by awarding offsets for installing N_2O abatement technologies in both new and existing plants. Depending on implementation, these policies may require expanded agency authority.

4.3. BLACK CARBON

GWP$_{20}$ = 3230
GWP$_{100}$ = 917
Atmospheric Lifetime = 1-2 weeks







References:
GWPs – Rypdal, 2009
Atmospheric Lifetime – IPCC, 2007
Historical emissions – RCP Database, 2009
Global sources – Bond et al., 2004
U.S. sources – Bond et al., 2004

4.3.1. Emission sources

Black carbon is one type of fine particulate matter included in PM2.5 (particulate matter with a diameter less than 2.5 um). It is primarily composed of carbon produced by the incomplete combustion of carbon-based fuels (van Setten et al., 2001).

Open biomass burning, such as wildfires and the burning of agricultural waste, account for approximately 42 percent of global black carbon emissions.

Contained combustion accounts for the remaining 58 percent of global emissions. Contained combustion emissions are produced by diesel and two-stroke engine operation (42 percent), industrial production and electricity generation (29 percent) and residential cooking and heating (29 percent) (Grieshop et al., 2009). Contained combustion emissions have decreased over time in OECD countries but have increased to a much greater extent in the rest of the world, and this trend is expected to continue for at least the next 40 years (Diesel, 2009). Though shipping only accounts for 1.7 percent of black carbon emissions, the amount emitted is expected to rise dramatically in sensitive areas such as the arctic (Lack et al, 2008).

4.3.2. Impacts of emissions

Black carbon emissions exert a strong influence on the climate. Black carbon is arguably the second strongest climate forcer after CO$_2$, exerting virtually all of its impact within weeks of its emission. The lifetime of black carbon ranges from a few days to weeks, and it can agglomerate and complex with other chemicals during this period (Baron et al., 2010). Black carbon is so named due to its strong absorption of incoming solar radiation, many orders of magnitude greater than CO$_2$. Black carbon GWP$_{100}$ estimates range from 460 to 1,320 (Fuglestvedt et al., 2010; Rypdal et al., 2009). The GWP values in the sidebar are mid-range estimate of global average GWP (McKinsey, 2009).

The climate effects of black carbon emissions are most pronounced in the short term because of its short atmospheric lifetime. For this reason, black carbon emissions reductions benefits calculated over a 20-year period are 3.5 times greater than those calculated over a 100-year period.

The climate impact of black carbon emissions is complicated by many co-emitted pollutants, including organic carbon which, although chemically similar to black carbon, has different optical properties resulting in a negative radiative forcing. The ratio of organic carbon to black carbon determines the net radiative forcing of carbonaceous particulate matter and varies with combustion characteristics. Open biomass burning results in a low ratio of black carbon to organic carbon emissions and hence less warming per unit black carbon emitted. Contained combustion results primarily in black carbon emissions and hence more warming per unit black carbon emitted.

In addition to the direct forcing caused by light absorption, black carbon has indirect effects such as decreasing snow, ice, and cloud albedo as well as affecting cloud formation. Black carbon deposition decreases snow and ice surface albedo, causing a local warming effect which can cause melting. Snow and ice melt can also expose low albedo rock or water surfaces, contributing to positive feedbacks in warming.

How black carbon emissions affect cloud formation is less well understood. On one hand, black carbon particles can act as cloud condensation nuclei and increase the formation of clouds which reflect solar radiation (Chen et al., 2010). On the other hand, black carbon particles darken clouds, decreasing their albedo, and they can stabilize the atmosphere hence reducing cloud formation (Jacobson, 2002; Ramanathan, 2007).

Thus, the climate impact of black carbon emissions depends on a variety of factors, including combustion characteristics, atmospheric dynamics, and geography. For instance, the climate impacts of open burning are reduced due to the co-emission of reflective organic carbon but are magnified by feedbacks when emissions occur in snow-covered regions, such as at high latitudes and in the Himalayas (Princeton, 2009). Despite uncertainty, researchers are confident that black carbon emissions from sources near snow and ice and from sources with low co-emission of organic carbon result in a net warming effect (Kopp and Mauzerall, 2010).

Black carbon emissions also impose human health risks because, as an aerosol, black carbon can embed in the lungs when inhaled. It is estimated that 1.8 million people die each year in developing countries due to black carbon and other emissions from indoor fires (Grieshop, 2009).

4.3.3. Current policies and policies under development

Health benefits associated with reducing emissions of fine particulate matter have historically been the main driver of policy efforts. Additionally, efficiency improvements in combustion-based devices have been a cost-effective driver of reductions in black carbon emissions.

Technology to reduce black carbon in the transportation sector is readily available. In the U.S., on-road vehicles model year 2010 and newer must meet strict PM2.5 emission standards which effectively reduce black carbon emissions over 99 percent. Off-road vehicles must meet similar standards starting in 2013.

Older vehicles can be retrofitted with diesel particulate filters which can also reduce black carbon emissions over 99 percent. However, ultra-low sulfur diesel fuel must be used for the filter to function properly. Ultra-low sulfur fuel is available in the U.S. and some other developed countries but is not available in many developing countries. EPA has a Diesel Retrofit Technology Verification program that lists EPA-tested retrofit technologies.

California has implemented several diesel particulate filter retrofit programs at significant cost. California also requires best available control technology to be used on heavy-duty road vehicles (over 14,000 pounds) and by 2014, requires 2010 model engines in these vehicles. California Air Resources Board (CARB) is now scaling back this initiative due to the economic downturn, which lowered emissions by reducing vehicle miles driven and intensified industry opposition to the regulations. A case study on California and New York City's diesel retrofit programs, along with further resources, can be found in Appendix I.

United Nations Environment Programme (UNEP) will soon release an integrated assessment report on black carbon. EPA and UNEP have also collaborated in the past on transportation and air quality capacity building.

Current U.S. and EU particulate matter emissions standards are based on mass rather than particle size. This may limit the regulations' climate change mitigation efficacy because smaller particles (1) comprise only a few mass percent of PM but over 99 number percent of particles and (2) have longer atmospheric lifetimes (van Setten et al., 2001).

The Global Alliance for Clean Cookstoves, a public-private initiative led by the United Nations Foundation, is currently pursuing reductions in black carbon emissions from cookstoves.

The UN's Convention on Long-range Transboundary Air Pollution, of which the U.S. is a member, has decided to include black carbon as an important consideration in its PM2.5 negotiations for April 2011.

4.3.4. Policy opportunities

4.3.4.a. Policy support for installation of diesel particulate filters in heavy-duty vehicles (*) – EPA could support retrofit projects of heavy-duty vehicles with diesel particulate filters. This could involve enhancing its Diesel Retrofit Technology Verification program to include information on model programs and best practices.

4.3.4.b. International cooperation to address black carbon emissions from brick kilns (*) – Black carbon emissions from this sector are significant and rapidly growing in many developing countries. Because of existing low cost, low technology solutions, McKinsey estimates that upgrading kiln technology is a net with negative cost abatement option (McKinsey, 2010). Agencies could work to support international cooperation on deployment of mitigation technologies.

4.3.4.c. International cooperation to reduce black carbon emissions that reach "hot spots" (*) – The Arctic and the Himalayas are black carbon "hot spots" meaning that black carbon that reaches these regions has a disproportionate effect on regional warming due to snow and ice albedo feedback cycles. Currently black carbon emissions from China, India and as far away as the Middle East and Europe are deposited in the Himalayas and the Tibetan Plateau (Kopacz et al., 2010). Higher levels of exploration, fossil fuel extraction and travel in the Arctic region in coming years due in part to ice melt will likely dramatically increase shipping and trucking in this sensitive region. The Arctic Council and the Convention on Long-range Transboundary Air Pollution could use their existing authority to work together to address increases in black carbon emissions and deposition in the Arctic.

4.3.4.d. International collaboration to share diesel fuel technologies with developing countries – The U.S. and EU have significantly reduced black carbon emissions from road transportation, but reductions in the developing world have been limited due to insufficient infrastructure. One example is the technology pair of ultra-low-sulfur diesel fuel and particle filters. The U.S. has used ultra-low-sulfur diesel fuel since 2007, at an approximate price premium of $0.08 per gallon through additional processing at refineries. However, fuel desulfurization technologies are not widely used outside of the U.S. and EU. Agencies could facilitate engagement among industries in developing countries to build this infrastructure. Vehicle emission control technology could be developed concurrently, so that low PM emitting vehicles can be rolled out along with ultra-low-sulfur diesel fuel; the United States undertook a similar rollout in 2007. Taking these steps could help developing nations avoid technological lock-in of high black carbon emitting transportation infrastructure. While the benefits of this collaboration might not emerge for several years, we highlight this opportunity because of its high potential for mitigation over the medium to long term.

4.3.4.e. Creation of an annual international meeting on black carbon – While black carbon has been increasingly discussed within existing international climate fora, a dedicated international meeting of black carbon scientists, engineers, and policy experts has not been organized. An annual conference could foster international research and development collaboration on black carbon climate science, mitigation technology, and policy.

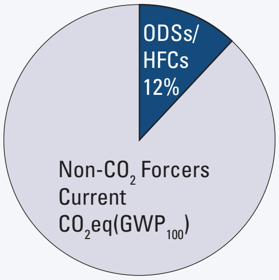
4.3.4.f. Tightening of vehicle efficiency standards to mitigate black carbon emissions – EPA not does currently consider the global warming potential of black carbon emissions from vehicles when regulating GHG emissions and fuel economy under the corporate average fuel economy (CAFE) standards. However, black carbon emissions are reduced when fuel economy standards are more stringent, especially with heavy-duty vehicles. This year, EPA and NHTSA announced a first-ever corporate average CAFE program for heavy-duty vehicles (EPA, 2010d). More stringent CAFE standards, particularly for heavy-duty vehicles, would reduce black carbon emissions by reducing vehicle fuel use.

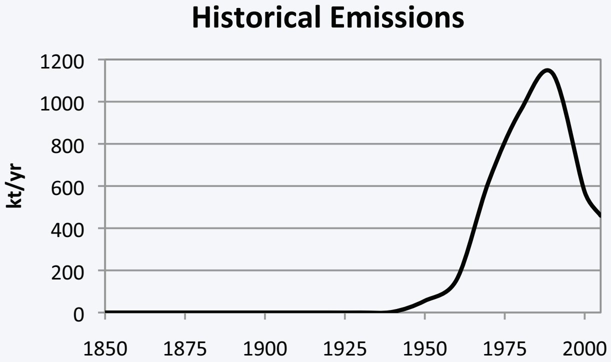
4.3.4.g. Expansion of funding for retrofit programs through loan guarantees for retrofits by small fleet operators and farms – Black carbon emissions from existing fleets and farm equipment can be mitigated with technology retrofits. Small fleet operators and farmers in particular may have difficulty financing the upfront costs. A loan guarantee program for black carbon mitigating retrofits could ensure access to capital (Princeton, 2009).

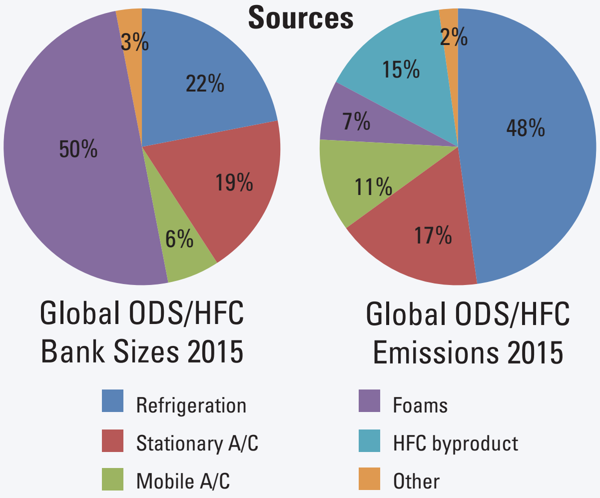
4.3.4.h. Addition of black carbon mitigation to the list of potential GEF projects – The Global Environment Facility (GEF) is an independent financial organization that partners with United Nations agencies, among others, to provide grants to developing countries for environmental projects. Projects to mitigate black carbon emissions present an opportunity for GEF to support cost-effective climate change mitigation.

4.4. OZONE DEPLETING SUBSTANCE (ODS) BANKS

Compound	GWP20	GWP100	Atmospheric Lifetime (yrs)
CFC-11	6730	3000	45
CFC-12	11,00	8100	100
HCFC-22	5160	1500	12
HCFC-123	273	90	1.3
HCFC-141b	2250	600	9.3
HCFC-142b	5490	1000	17.9







4.4.1. Emission sources

Although 97 percent of the production and consumption of high-GWP ozone-depleting substances (ODSs) have been phased out by the Montreal Protocol, significant quantities of ODSs remain in previously consumed equipment and appliances such as commercial and domestic refrigerators, mobile and stationary air-conditioning equipment, building and appliance foam insulation, fire suppression systems, and stockpiles (EIA, 2009). These reservoirs of ODSs, known as ODS banks, are continually leaking and have potential to significantly contribute to global climate change if not recovered and destroyed.

In 2002, the greenhouse gas storage in ODS banks was 19 GtCO$_2$eq. For a typical ODS bank unit, the average time to complete release of banked gas is on the order of twenty years.

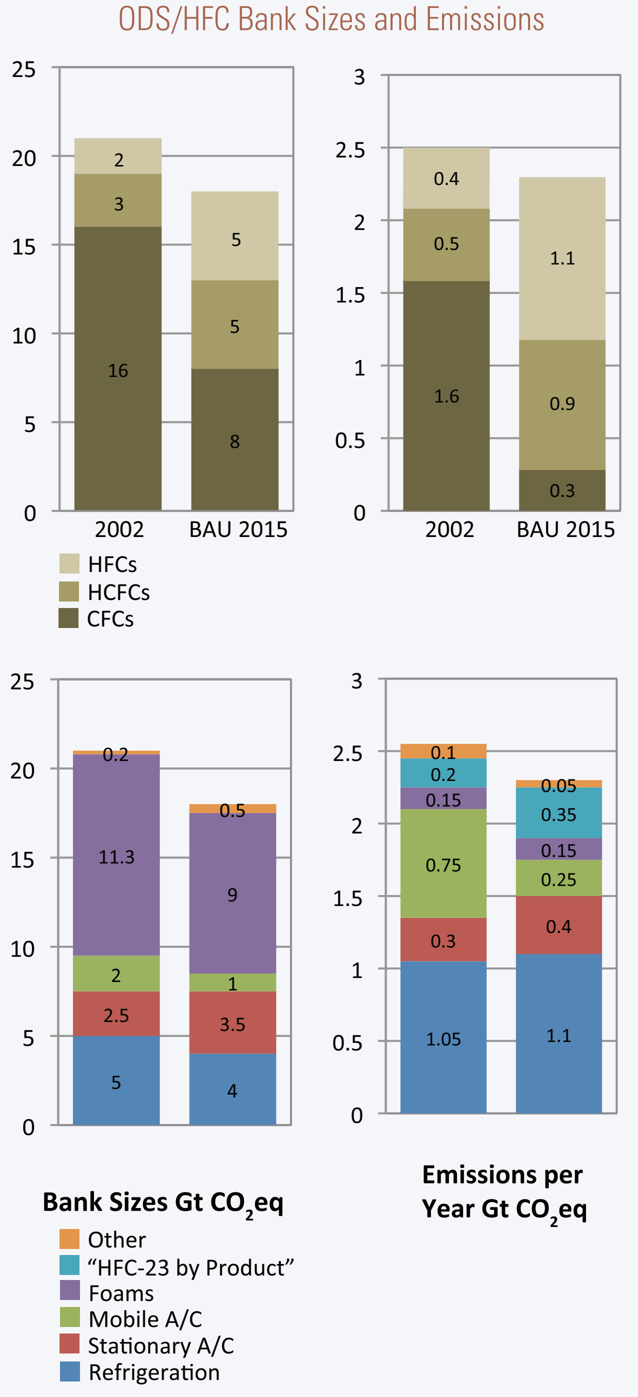
Although the majority of banks are in foams, the majority of emissions are from the refrigeration and air-conditioning sectors due to faster leakage rates. Fortunately, collection of ODS banks from these sectors is also the least technologically challenging and labor intensive. The greenhouse gas storage in these “reachable” fast-emitting bank sectors is 8.9 GtCO$_2$eq (5.1 and 3.8 GtCO$_2$eq developing and developed nations respectively) (TEAP, 2009).

4.4.2. Impacts of emissions

ODS bank emissions have the potential to exert a significant influence on climate. If no action is taken to address ODS banks, the majority of currently banked ODSs will be released into the atmosphere within a decade. The associated projected emissions of 6 GtCO$_2$eq are equal in magnitude to the total emissions reductions under the first commitment period of the Kyoto Protocol (IPCC/TEAP, 2005).

4.4.3. Current policies and policies under development

ODS management programs exist in several countries. The Montreal Protocol has approved 12 destruction technologies, and destruction facilities are present in 28 countries (TEAP, 2009). Japan alone has 82 facilities using ten different destruction technologies (ICF, 2008). In addition, the Multilateral Fund has financed over 100 projects in part to support international technology diffusion (EIA, 2009). Projects have been fast-acting, taking on the order of several months to initiate (Cohen et al., 2010).



ODS and HFC bank sizes and emissions in 2002 and projected for business-as-usual 2015. Sizes and emissions are broken up by chemical species and sector. *Source: adapted from TEAP/IPCC 2005.*

In the U.S., EPA's Responsible Appliance Disposal program, initiated in 2006, helps protect the climate and ozone layer by requiring partners to recover ODSs in expired equipment. In addition, the Expanding Industrial Energy Efficiency Incentives Act of 2009, which includes tax credits to improve energy efficiency and to replace existing CFC chillers, is currently under review (McQuade, 2010). DOE's Cash for Appliances program also provides incentives for replacing old refrigerant equipment. However, since both of these initiatives aim to improve energy efficiency, the disposal of old equipment is not mandatory.

Voluntary programs have had varying levels of success, with hurdles arising from locating and securing products and equipment, lack of enforcement, sparsely populated areas and island transport costs, financial restraints, and disputed "best practices" and methodologies. Germany, for instance, is viewed as having the most advanced voluntary ODS recycling efforts, and still only recovers 25 percent of ODS banks (Mate, 2010). A case study of a successful ODS phase-down program through a public-private partnership, along with further resources, can be found in Appendix I.

Currently, there is no global regulatory authority over bank recovery and removal. Although proposals have existed within the Montreal Protocol since 2009 to expand its regulation to include the environmentally sound management of ODS banks, the only outcome has been a development of contact groups to further look into this possibility. The Multilateral Fund is currently replenishing its funding and will soon decide whether to allocate funding for ODS bank management.

4.4.4. Policy opportunities

The management of ODS banks presents a promising opportunity for fast climate change mitigation, with the co-benefit of protecting the stratospheric ozone layer with associated benefits to human health. TEAP (2009) estimates average removal costs between $10 and $35 per t$CO_2$eq, which is competitive with other greenhouse gas reduction measures. However, upfront costs may be a barrier to removal projects.

4.4.4.a. DOE expansion and modification of Cash for Appliances program (*) – Under the Cash for Appliances program (see case study in appendix), DOE allocated $300 million to states for the provision of consumer rebates energy-efficient appliance purchases. Key program design elements, including the rebate amount and disposal requirements, were under state purview. As a result, there is a wide range in state requirements of proof of recycling: Some states require requirement of proof of recycling of old equipment, others offer bonuses for submitting proof of recycling, and others do not require proof of recycling (Schultz, 2009).

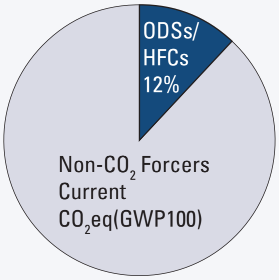
DOE could expand this program while requiring that states verify the safe disposal of ODS banks. Alternatively, DOE could require that any new rebates only apply to purchases from retailers that are voluntary partners in EPA's Responsible Appliance Disposal program. Currently, only three retailers are partners in the program.

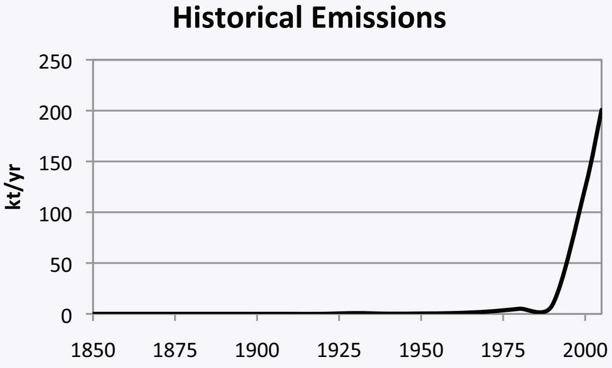
4.4.4.b. Establishment of financial support for ODS bank removal projects in developing countries – To facilitate the removal of ODS banks in developing counties, financial support could be provided to offset upfront project costs. Financing could come from (1) revenue from carbon markets associated with the destruction of banks in developed countries; (2) the Multilateral Fund; (3) a separate funding facility for ODS bank recovery and destruction partnered with the Multilateral Fund under the Montreal Protocol; (4) taxation of imports or sales of synthetic refrigerants with global warming potential.

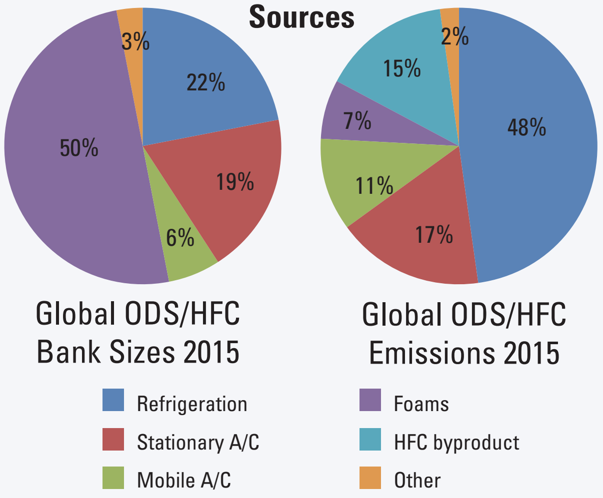
Australia currently funds ODS bank recovery and destruction by taxing imports of ODSs with global warming potential at 1 AUD per kilogram under the Refrigerant Reclaim Australia (RRA) program (see case study in appendix). A similar program could be more challenging to implement in the U.S. because the U.S., unlike Australia, is both a major producer and an importer of refrigerants.

4.5. HYDROFLUOROCARBONS (HFCs)

Compound	GWP_{20}	GWP_{100}	Atmospheric Lifetime (yrs)
HFC-134a	3830	1,300	14
HFC-152a	437	140	1.4
HFC-245fa	3380	1,300	8
HFC-23	12000	11700	270
HFO-1234yf	-	4	11 days







Global ODS/HFC Bank Sizes 2015

Global ODS/HFC Emissions 2015

References:

GWPs & Lifetimes – TEAP, 2010; Freedonia, 2009
Historical emissions – RCP Database, 2009
Bank size & emissions – TEAP/IPCC, 2005

4.5.1. Emission sources

Hydrofluorocarbons (HFCs) were developed as the next generation of alternative refrigeration and foam blowing chemicals in response to the phase-out of the ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) under the Montreal Protocol. The main sectors that consume HFCs are refrigeration and air conditioning, industrial solvents, foams, aerosols, and fire extinguishing. HFCs are also produced as a by-product during the production of HCFC-22. In each of the sectors, emissions occur at a variety of stages during the product lifetime, such as manufacture, use (including leaks, purges, and failures), service, and disposal.

Across all sectors, HFC-134a is the predominant HFC, accounting for about two-thirds of all HFC consumption (Atlantic Consulting, 2004). Refrigeration and air conditioning account for the majority of HFC consumption and emissions. Refrigeration and air conditioning are also projected to dominate consumption growth and to constitute 80 percent of global fluorinated-gas emissions by 2050 (Gschrey and Schwarz, 2009).

4.5.2. Impacts of emissions

HFC emissions exert a small but growing influence on the climate. HFCs have zero ozone depleting potentials (ODPs) but their GWPs are similar or even higher than those of the CFCs and HCFCs they are replacing. While HFCs currently account for less than 2 percent of total greenhouse gas emissions for the United States, their emissions are projected to double by 2020 as HCFCs are phased out (EPA, 2009b). A recent study estimates that developing country emissions will exceed those of developed countries by up to 800 percent in 2050, contributing up to 20 percent of total CO_2-equivalent emissions if unabated (Velders et al., 2009).

4.5.3. Current policies and policies under development

In the U.S., individual agencies and region-based initiatives have addressed HFCs separately; there is no overarching domestic regulation of HFCs that addresses all sectors.

EPA administers the Significant New Alternatives Policy (SNAP) program, which approves alternatives to CFCs and HCFCs, including all currently approved HFCs. Some lower-GWP alternatives have been approved for specific uses, while other low-GWP alternatives and natural refrigerants are pending approval; more detail is provided in Table 4.5.1.

In 2010, EPA and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) finalized a rule under the Clean Air Act establishing greenhouse gas emissions standards and new fuel economy rules for light duty vehicles that allow auto manufacturers to receive a credit toward meeting fuel economy standards if they use low-GWP refrigerants until model year 2016 (Bianco and Litz, 2010).

DOE has proposed a policy to adopt full fuel cycle accounting of energy in the analysis of appliance standards. This proposed policy does include some non-CO_2 climate forcers, but does not include HFCs (DOE, 2010a). In addition, the Federal Trade Commission and DOE are working together to revise energy labels.

The California Air Resources Board has instituted HFC emissions reduction measures for motor vehicle air conditioning. This regulation restricts the use of HFC-134a in all vehicle classes and recommends CO_2 as a viable alternative, similar to the EU Directive discussed next. The rule also includes regulation to control emissions from small containers of automotive refrigerants (CARB, 2010).

In 2006 the European Commission announced the "F-gas Directive," new standards for refrigerants used in mobile air conditioning. (The term "F-gases" refers to fluorinated greenhouse gases, including HFCs, PFCs and SF_6.) The directive bans the use of HFCs with GWP_{100} over 150 for retrofits in existing vehicles; the requirement is phased in for new vehicles, along with new standards for leakage rates and test procedures (EC, 2006). The main chemical affected is HFC-134a. To comply with this directive, individual countries have set HFC regulations. Austria and Denmark have restricted the production of HFCs towards an eventual phase-out with specific target dates, while Sweden and the Netherlands have focused on containment strategies to reduce chemical leakage from equipment. Norway charges consumers a fee for the GWP of HFCs in purchased products and then issues a refund upon the return of equipment for proper destruction (Hekkenberg et al., 2007).

HFCs are one of the six categories of greenhouse gases controlled under the UNFCCC Kyoto Protocol (UNFCCC, 1997).

Chemical	GWP_{100}	Atmospheric Lifetime	Sector	Advantages	Drawbacks	SNAP Approved?
HFC-152a	53	1.4 years	Air conditioning Refrigeration	Drop-in	Still an HFC	new MVAC, new domestic
HFO-1234yf	4	11 days	MVAC	Drop-in Short atmospheric lifetime	HCFC precursor Expensive, Flammable	No
CO_2	1	~ 100 years	MVAC Supermarket refrigeration	Natural, Cheap, Safe	High temperature uses need new systems	new retail, industrial, new cold storage, new domestic
Ammonia	0	few hours	Air conditioning Refrigeration	Natural, Cheap, Efficient, Short atmospheric lifetime	Toxicity Flammability	new chillers, storage, new retail, domestic retrofit, new industrial
Hydro-carbons	5	weeks, months	Foams Domestic refrigerators Coolers, Vending	Natural, Cheap, Efficient, Short atmospheric lifetime	Toxicity Flammability	retrofit, new low temp refrig. retrofit, new industrial refrig.

Table 4.5.1: Table highlighting the low-GWP alternatives and natural alternatives for high-GWP HFCs. SNAP approval status from EPA, 2010e.

During the 16th Conference of the Parties to the UNFCCC in 2010, the Consumer Goods Forum announced its intention to ban the use of high-GWP refrigerants, mainly HFCs, by 2015 and to replace them with natural refrigerants. Natural refrigerants include ammonia, CO_2, and hydrocarbons. The forum includes 400 global manufacturers and retailers including Unilever, Coca-Cola, Tesco, and Carrefour.

Since HFCs exist as replacements for CFCs solely due to the Montreal Protocol's resolutions, it is arguable that HFCs fall under the jurisdiction of the Montreal Protocol. The Montreal Protocol has acted on climate grounds before, by accelerating the phase-out of HCFCs that have minimal ODPs but high GWPs. Two similar proposals to regulate HFCs under the Montreal Protocol were submitted for consideration at the November 2010 Meeting of the Parties: a joint proposal from the United States, Canada, and Mexico, termed the North American Proposal, and a proposal from the Federated States of Micronesia. Both proposals outline a phase-down of HFCs similar to past reductions of CFCs and HCFCs, with a lag time for developing countries (UNEP, 2010b, and UNEP, 2010c). While neither proposal was adopted in 2010 due to concerns about the availability of alternative technologies and proper financial support, 91 countries voiced support for the proposals. Proponents remain confident that HFCs will be regulated under the Montreal Protocol in the next several years. A case study about expanding the Montreal Protocol and a voluntary HFC reduction undertaking, along with further resources, can be found in Appendix I.

4.5.4. Policy opportunities

Many of the following options suggest a transition to lower-GWP HFCs or natural refrigerants which include CO_2, ammonia, and/or hydrocarbons. Table 4.5.1 highlights the alternatives to high-GWP HFCs and their respective advantages and drawbacks. Additional information regarding high-GWP HFC alternatives and their abatement potentials is presented in the appendix of this report.

The diversity of existing regulations and initiatives to ban HFCs or curb their growth emphasize the momentum to firmly address HFCs. If the United States tackles HFCs as a fast-action mitigation strategy, it would send a strong signal to the world that international HFC regulation is possible and imminent. Demonstrated leadership from the United States on HFC initiatives could build support for the North American Proposal under the Montreal Protocol.

4.5.4.a. EPA withdrawal of SNAP approval of HFC-134a (*) – EPA could rescind SNAP approval of HFC-134a. This action has recently been petitioned by the NRDC, Institute for Governance and Sustainable Development (IGSD), and Environmental Investigation Agency (EIA).

4.5.4.b. EPA and NHTSA incorporation of low-GWP refrigerant credits for medium-duty, heavy-duty, and off-highway vehicle classes (*) – EPA and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) could expand new vehicle emission regulations that include credits for low-GWP refrigerants of HFCs for light-duty vehicles to other vehicle classes.

4.5.4.c. Engagement with large commercial cooling and retail food refrigeration industries to reduce HFC leakage in existing and new equipment (*) – Refrigeration and cooling represents the sector with the largest abatement potential for HFCs. Agencies could engage suppliers, installers, and purchasers of cooling and refrigeration equipment to promote available technologies for leakage reduction.

4.5.4.d. Establishment of voluntary GWP standards for refrigerants under the EPA Greenchill partnership – Greenchill is an EPA partnership with food retailers to reduce refrigerant emissions by incorporating low-GWP alternatives and reducing charge size and leakage. The EPA Greenchill partnership could establish voluntary standards for acceptable GWP values for refrigerants to use in new supermarkets, or other subsectors.

4.5.4.e. Climate impact labeling – Climate impact information that includes HFCs could be incorporated in product labels through the Energy Star program or Energy Guide labels to encourage companies to use lower GWP alternatives.

4.5.4.f. Mandatory certification for HFC sales and service – EPA could promulgate a regulation that requires all technicians and individuals that handle refrigerants to receive certification. Sales of HFCs could also be restricted to certified individuals. In this United States, this certification is already required for CFCs and HCFCs (EPA, 2006a).

4.5.4.g. Mandatory HFC-23 destruction – EPA could require the destruction of HFC-23 byproduct emissions. This policy may require an amendment to the Clean Air Act.

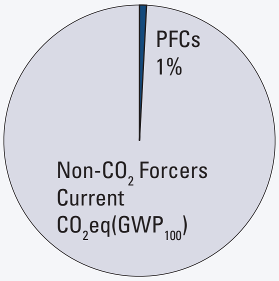
4.5.4.h. Implementation of a cap on HCFCs and HFCs through amendment of the Clean Air Act – Subtitle C of the American Power Act, introduced by Senators

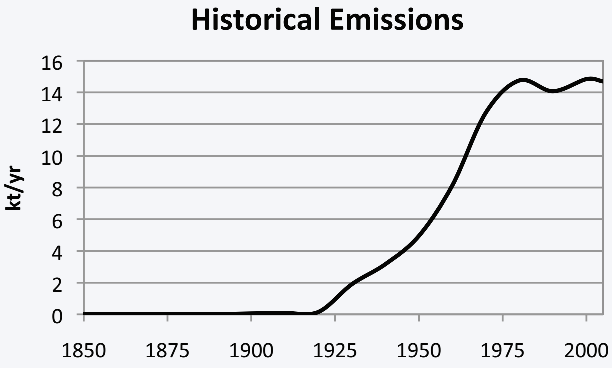
John Kerry and Joseph Lieberman in 2010, would have amended Title VI of the Clean Air Act to include several HCFCs and HFCs as Class II substances. This section of the bill has industry support and could face less political resistance than the bill as a whole. Production, consumption, and importation would be capped and gradually phased-down using to-be-determined allowances and offset credits, with an end-goal of 85 percent reduction by 2032.

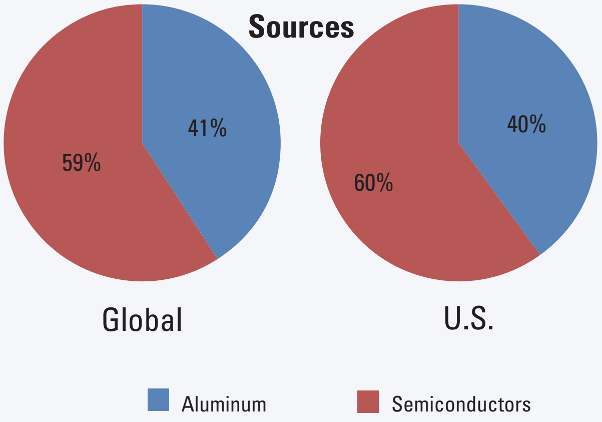
4.5.4.i. DOE support for research and development of HFC alternatives – Numerous alternatives to high-GWP HFCs are readily available for widespread incorporation into multiple sectors. However, a main challenge remains the long approval process for new chemicals and the slow continued development of safe natural refrigerants. DOE could fund research and development of low-GWP alternative chemicals by industry. Specifically, research funding could be directed to explore alternatives to vapor compression technology, such as solid refrigerants. EPA could take steps to speed up the approval process under the SNAP program, such as creating a fast-track approval process for alternative refrigerants in high-priority sectors.

4.6. PERFLUOROCARBONS (PFCs: CF_4, C_2F_6, and C_3F_8)

Compound	GWP_{20}	GWP_{100}	Atmospheric Lifetime (yrs)
CF_4	3920	>7,390	>50,000
C_2F_6	8110	>12,200	>10,000
C_3F_8	5940	>8,830	>2,600







References:
GWPs & Lifetimes – Muhle et al., 2010; TEAP/IPCC 2005
Historical emissions – RCP Database, 2009
Global sources – EPA, 2006
U.S. sources – EPA, 2010

4.6.1. Emission sources

The three most prevalent long–lived, high-GWP PFCs are: tetrafluoromethane (CF_4, PFC-14), hexafluoroethane (C_2F_6, PFC-218), and octofluoropropane (C_3F_8, PFC-218). The majority of PFC emissions are anthropogenic, and there are no known natural sources of C_2F_6 or C_3F_8 (Muhle et. al., 2010).

Historically, the majority of CF_4 and C_2F_6 emissions have been byproducts of anode effects during aluminum production. Anode effects produce PFCs when voltage changes during aluminum electrolysis cause fluoride-containing molten salts to electrolyze. Although PFC emission rates from aluminum production have declined as a result of technological advances, PFC emissions in the atmosphere from aluminum production continue to grow in absolute terms, especially as aluminum production continues to expand in developing countries and because of the long atmospheric lifetime of PFC emissions."

PFCs are increasingly used in and emitted by semiconductor and electronics manufacturing processes such as plasma etching and chemical vapor deposition chamber cleaning. Atmospheric concentrations of PFCs are orders of magnitude higher than what would be expected based on reported industry emissions data. Emissions data for these gases are incomplete, especially for developing countries, despite efforts by the International Aluminum Institute (IAI) and the Asia-Pacific Partnership.

PFC emissions are expected to grow significantly over the next decade in large part due to increasing emissions from Asia. Recent data from observational sites in Japan indicate that China alone may account for 20 percent of global CF_4 emissions, 40 percent of C_2F_6 emissions, and 70 percent of C_3F_8 emissions, reflecting the rapid expansion of semiconductor and electronics production in China since the late 1990s (Saito et al., 2010).

4.6.2. Impacts of emissions

PFC emissions currently exert a relatively minor influence on the climate. However, the climate effects of PFC emissions are potent on a per-unit basis due to high global warming potentials and are effectively permanent due to long atmospheric lifetimes (Muhle et. al., 2010).

4.6.3. Current policies and policies under development

Semiconductor industry consortia, including the World Semiconductor Council (WSC) and International SEMATECH, have taken voluntary steps to reduce PFC emissions. The WSC was established in 1996 and consists of semiconductor industry associations in China, Chinese Taipei (Taiwan), Europe, Japan, Korea, and the U.S. In April 1999, WSC set a voluntary goal to reduce PFC emissions from semiconductor facilities by 10 percent or greater by the year 2010. At the time of print, it is not known whether WSC has achieved this goal.

Governments and industry across the globe have sponsored various efforts to reduce PFC emissions from aluminum production. Since the 1990s, EPA has collaborated with American aluminum producers to reduce PFC emissions from aluminum production under the Voluntary Aluminum Industrial Partnership.

The EU is currently working to develop a more comprehensive policy on PFC emissions through its F-Gas Directive. PFCs will be included for trading under the EU Emissions Trading Scheme starting in 2013.

The International Aluminum Institute (IAI), whose 27 member companies represent over 80 percent of global primary aluminum production, has led efforts to reduce PFC emissions. In the early 1990s, IAI set a voluntary goal of reducing PFC emissions per metric ton aluminum produced by 80 percent by 2010 from a 1990 baseline. This was achieved in 2006, primarily by building new smelting capacity with technologies like Point Feed Prebake (PFPB) systems that decrease the occurrence of anode effects. Despite these advances, there remains a wide range of performance within PFPB production systems, with the most efficient PFPB facilities operating at a level 10 times better than the median performance of PFPB operators (IAI, 2009). In 2006, IAI members adopted a new goal of reducing PFCs per metric ton of aluminum by at least 50 percent by 2020, compared to a 2006 baseline (Marks and Bayliss, 2010). A case study of Brazil's effective aluminum recycling efforts, along with further resources, can be found in Appendix I.

EPA, the World Resources Institute, the World Business Council on Sustainable Development, and IAI have collaboratively developed a set of protocols for measuring, accounting, and reporting GHGs from the aluminum sector.

PFCs are one of the six categories of greenhouse gases controlled under the UNFCCC Kyoto Protocol (UNFCCC, 1997). To date there have been five Clean Development Mechanism projects to reduce PFC emissions from aluminum production.

As a result of international efforts and technology improvements, reported annual PFC emissions from aluminum production have dropped from 96 $MtCO_2eq$ in 1990 to 22 $MtCO_2eq$ in 2009, despite an increase in aluminum production over the same period (Marks and Bayliss, 2010).

4.6.4. Policy opportunities

4.6.4.a. International cooperation to identify financing mechanisms for aluminum smelter retrofits in developing countries (*) – Retrofit technology to reduce PFC emissions from existing plants is relatively inexpensive and well-established. International cooperation to retrofit plants could reduce projected absolute growth in PFCs emissions from aluminum production in developing countries.

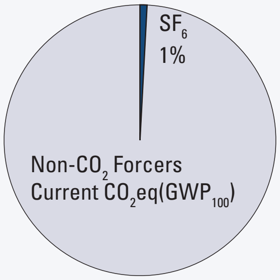
4.6.4.b. International cooperation to reduce PFC emissions from electronics and semiconductor manufacturing (*) – Electronics and semiconductor manufacturing are relatively young industries, and governments could work with these industries to address their long-lived emissions. As a starting point, government and industry could establish a forum for tracking and aggregating information on PFC use and emissions. This forum could also facilitate the sharing of information, technologies, best practices, and policy ideas to reduce PFC use and/or emissions. Such cooperation could take place through an existing forum for cooperation, like the Clean Energy Ministerial, as indicated in the recommendation in Section 5.2, and could also address SF_6 and NF_3.

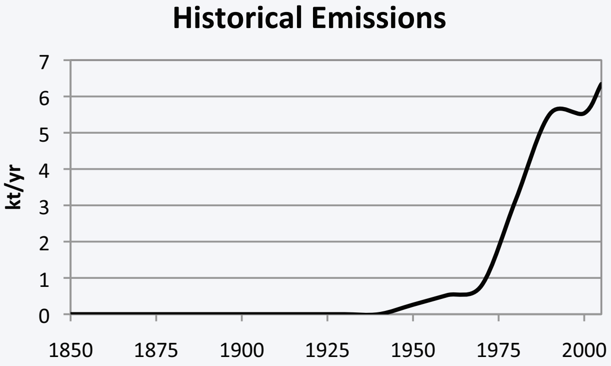
4.6.4.c. Establishment of ambitious domestic and international aluminum recycling goals – Currently, only roughly a third of the global aluminum waste streams is recycled. Increases in aluminum recycling rates could decrease the demand and production of primary aluminum. Aluminum recycling produces zero PFCs and only 5 percent of the GHG emissions of primary production. Setting new domestic and international goals or recycling standards could decrease PFC emissions from the aluminum industry.

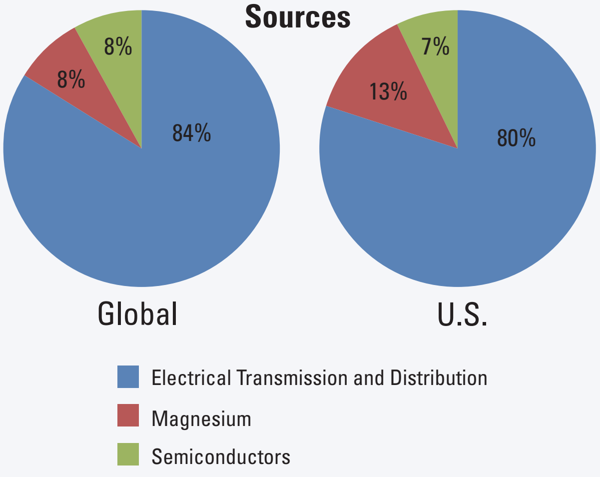
4.6.4.d. Development of international standards for anode effects during aluminum production – EPA could work with other governments and with industry to develop a voluntary standard that would become more stringent over time for the rate of anode effects in aluminum manufacturing. Anode effects are linearly related to PFC emissions from aluminum production.

4.7. SULFUR HEXAFLUORIDE (SF_6)

GWP_{20} = 16,300
GWP_{100} = 22,800
Atmospheric Lifetime = 3,000-50,000 years







References:
GWPs & lifetime – IPCC, 2007
Historical emissions – RCP Database, 2009
Global sources – EPA, 2006
U.S. sources – U.S. Climate Action Report, 2010

4.7.1. Emission sources

Sulfur hexafluoride (SF_6) is a highly stable gaseous compound that is colorless, odorless, non-toxic, non-flammable, and chemically inert, and has a high dielectric strength. These properties make SF_6 an attractive gas for industrial applications including use as an insulator in capacitors (Maiss and Brenninkmeijer, 1998).

Currently, the majority of SF_6 is used in electric power systems (75-80 percent of global sales of SF_6) and most of the remainder is used in magnesium production and semiconductor and thin film manufacturing (Smythe, 2000). A relatively small quantity of SF_6 is used as a filler gas in various consumer applications (e.g. tennis balls, athletic shoes, and soundproof windows) and for scientific and military applications (Olivier and Bakker, 1998).

Atmospheric levels of SF_6 have risen rapidly since industrial production began in 1953. Emissions of SF_6 occur because of venting or leakage of SF_6 from industrial applications. The contributions to total SF_6 emissions from each industrial sector are roughly proportional to SF_6 use, despite the fact that the emissions mechanisms are distinct (Smythe, 2000). While sales figures are an available proxy for the breakdown of end uses, significant quantities of SF_6 are likely sold between sectors. For example, the literature cites a trend of the electric power system sector selling to magnesium producers (Olivier and Bakker, 1998).

A recent study that compares a new top-down model of annual SF_6 emissions based on observations of atmospheric concentration with emissions reported by UNFCCC Annex I countries demonstrates that emissions reported in inventories likely underestimate the true emissions (Levin et al., 2010).

4.7.2. Impacts of emissions

SF_6 emissions currently exert a relatively minor influence on the climate. However, the climate effects of SF_6 emissions are potent on a per-unit basis due to its high global warming potential and are effectively permanent due to its long atmospheric lifetime. SF_6 is the most powerful greenhouse gas known, with a GWP_{100} of 23,900 and an atmospheric lifetime of 3,200 years (EPA, 2010a).

4.7.3. Current policies and policies under development

EPA currently administers voluntary programs to address

SF_6 emissions. EPA administers the SF_6 Emissions Reduction Partnership for Electric Power Systems. Under this program, EPA partners with the electric power and SF_6 industries to generate data on SF_6 sales and fosters collaboration by organizing conferences. Partners representing approximately 45 percent of electrical transmission miles have reduced their emissions by approximately 61 percent from 1999 to 2008 (EPA, 2010a).

EPA partners with magnesium producers and casters to develop inventory methodologies, develop and deploy emission reduction technologies, and evaluate cover gas alternatives under the SF_6 Emissions Reduction Partnership for the Magnesium Industry. Under this program, partners annually report their SF_6 emissions and make cost-effective reductions of those emissions; EPA provides technical and research assistance, facilitates technical information sharing, records and verifies the progress of partnering companies, and provides public recognition for reductions achievements (EPA, 2001). While many magnesium companies in the U.S. began to report emissions under this program, most continue to use SF_6 as their cover gas (EPA, 2010a).

Norway, Switzerland, Iceland, and Japan mandate that electric utilities administer leak detection and repair programs and administer mandatory SF_6 recycling programs.

SF_6 is one of the six greenhouse gases controlled under the UNFCCC Kyoto Protocol (UNFCCC, 1997). To date, five Clean Development Mechanism projects have been registered and one additional project is under review. The European Union's 2006 F-Gas Directive mandates the replacement of SF_6 with sulfur dioxide (SO_2) in magnesium production and casting, mandates leakage control and end-of-life recollection and recycling of gases in mid- to high-voltage switching equipment, and bans the use of SF_6 as a filler gas for consumer applications (Höglund-Isaksson et al, 2010).

4.7.4. Policy opportunities

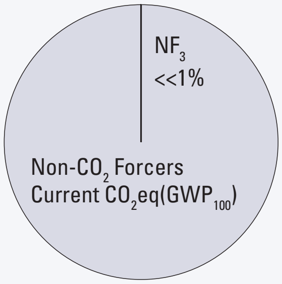
4.7.4.a. Agency administration of SF_6 recycling programs and required leak detection and repair programs in the electric power system sector – Electric power systems account for approximately 75-80 percent of annual global sales of SF_6 and a proportional share of SF_6 emissions (Smythe, 2000; EPA, 2006a). Because SF_6 is uniquely efficient and cost effective in this application, substitutes for SF_6 are not widely considered. EU, Norway, Switzerland, Iceland, and Japan currently administer SF_6 recycling programs and mandate that utilities administer leak detection and repair programs. EPA estimates that 49 and 7 percent of the current baseline SF_6 emissions remain available to abatement through recycling and leak detection and repair respectively. EPA could similarly administer an SF_6 recycling program and require utilities to administer leak detection and repair programs.

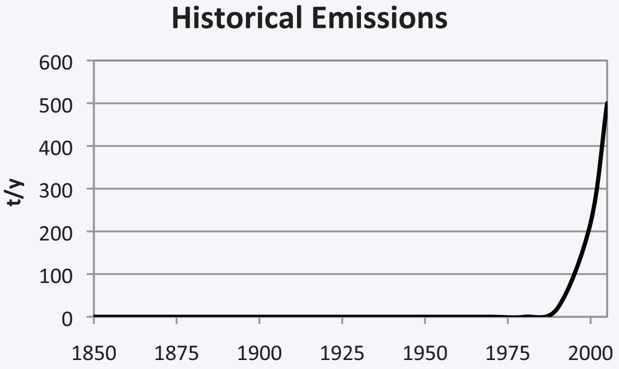
4.7.4.b. Partnership with industry to support efforts to reduce SF_6 emissions from semiconductor and thin film manufacturing – The use of SF_6 in manufacturing processes accounts for approximately 5-10 percent of annual global sales of SF_6 and approximately a proportional share of emissions (Smythe, 2000). There are various existing and emerging technologies that can reduce the emissions of SF_6 from manufacturing processes including: point-of-use plasma abatement, capture and recovery, catalytic decomposition, thermal processing and destruction, and replacement of SF_6 with onsite fluorine gas production (EPA, 2006a; De Wild-Scholten, 2007; Lai, 2008). EPA could establish a partnership with industry to develop and deploy these technologies, analogous to its partnership with the magnesium industry.

4.7.4.c. International engagement to promote alternative cover gases in magnesium production – Magnesium production accounts for approximately 5-10 percent of annual global sales of SF_6 and approximately a proportional share of emissions (Smythe, 2000; Palmer, 1998). The use of alternative cover gases such as SO_2 or other fluorinated gases (e.g. Novec 612, AM-cover, and HFC-134a) could reduce SF_6 emissions from the magnesium production sector. Agencies could engage with developing countries with high projected growth in magnesium production, in particular China, to promote the use of alternative cover gases.

4.8. NITROGEN TRIFLUORIDE (NF_3)

GWP_{20} = 12,200
GWP_{100} = 16,800
Atmospheric Lifetime = 740 years





Sources

- Semiconductors
- Electronics
- Thin film manufacturing processes
    - plasma etching
    - chemical vapor deposition chamber cleaning

References:
GWPs & lifetime – IPCC, 2007
Historical emissions – RCP Database, 2009

4.8.1. Emission sources

NF_3 use was initially limited to rocket fuel and laser applications. When PFCs were added to the Kyoto Protocol's basket of gases, NF_3 was introduced as a replacement. NF_3 is now used in and emitted by semiconductor, electronics, and thin film manufacturing processes such as plasma etching and chemical vapor deposition chamber cleaning. For example, NF_3 replaced C_2F_6 as a cleaning agent in electronics manufacturing because, despite the fact that NF_3 has a higher GWP, it breaks down more readily during manufacturing processes resulting in reduced emissions. Estimates suggest that approximately 2-3 percent of NF_3 process gas is emitted to the atmosphere, compared to 60 percent of C_2F_6 in analogous manufacturing processes (Robson et al. 2006; Lee et al. 2007).

4.8.2. Impacts of emissions

NF_3 emissions currently exert a relatively minor influence on the climate. However, the climate effects of NF_3 emissions are potent on a per-unit basis due to its high global warming potential and are effectively permanent due to its long atmospheric lifetime. NF_3 has a GWP_{100} of 16,800 and an atmospheric lifetime of 550 years (EPA, 2010a).

NF_3 emissions are also rapidly growing. Atmospheric concentrations of NF_3 are much higher than would be expected based on limited industrial emissions data and have grown at 11 percent per year. 2008 emissions are about 10 $MtCO_2$eq per year, but given the current growth rate of the industry, NF_3 emissions could surpass those of SF_6 and PFCs (35 and 42 $MtCO_2$eq, respectively, for 2005 Annex I emissions) this decade (Weiss et al., 2008).

4.8.3. Current policies and policies under development

As of November 2010, EPA requires reporting of NF_3 emissions from electronics manufacturing and fluorinated gas production facilities that emit 25,000 tCO_2eq or more (EPA, 2010f).

In international climate negotiations, some parties, including Association of Small Island States countries, have called for NF_3 to be included in the post-Kyoto basket of GHGs (UNFCCC, 2010).

4.8.4. Policy opportunities

4.8.4.a. International collaboration on NF_3 emissions reductions through a task force on non-CO_2 climate forcers – International collaboration through a task force on non-CO_2 climate forcers could facilitate collaboration on industrial best practices for minimizing NF_3 emissions during production and end-use and could also foster research into more potential replacements to NF_3, particularly replacements that can be more easily transported than the primary current alternative, fluorine gas (F_2). Fluorine gas currently must be produced on-site due to its reactivity and toxicity. Potential cost savings associated with reducing the emissions losses of NF_3, which is currently priced at about $20 per kilogram, provide an incentive for industry participation (Prather et al. 2008). This collaboration could take place through an existing forum for cooperation, like the Clean Energy Ministerial, as indicated in the recommendation in Section 5.2, and could also address PFCs and SF_6.

4.8.4.b. EPA expansion of NF_3 emissions reporting requirement to all sectors – Currently, EPA only requires NF_3 emissions reporting from end-use applications in electronics manufacturing. However, the life cycle emissions of NF_3 from its manufacture to its end use have been shown to be relatively significant (Fthenakis et al., 2010). EPA could require reporting for all industries using and producing NF_3.

4.8.4.c. Establishment of sectoral caps on NF_3 emissions – The EU currently establishes sectoral emissions caps using a benchmark based on the average emissions of the 10 percent best performing European installations (an "average best 10 percent policy"). The EU has not established sectoral caps for NF_3 emissions because the EU Emissions Trading Scheme currently covers only large point sources of greenhouse gas emissions. However, EPA could employ similar sectoral caps on NF_3 emissions. This policy may require expanded agency authority.

4.9. ROOF AND PAVEMENT REFLECTIVE AND EMISSIVE PROPERTIES

Roofs and paved surfaces—including roads, parking lots, and sidewalks—are estimated to cover more than 0.6 percent of global land area. Roofs in urban areas are estimated to cover 380,000 square kilometers of global land area, and paved surfaces in urban areas are estimated to cover an additional 530,000 square kilometers (Akbari et al., 2008). Paved surfaces are estimated to cover approximately 115,000 square kilometers (1.2 percent) of land area in the United States (USDA, 2006; FHWA, 2010; Davis et al., 2010). The extent of paved and built surface area will continue to increase in conjunction with economic development and urbanization in developing countries (Ingram and Liu, 1997; Tan et al., 2005).

4.9.1. Cool roof and cool pavement technologies

A direct reduction in radiative forcing can be achieved by increasing the fraction of solar energy that is reflected by roofs or paved surfaces.

The fraction of solar energy that is reflected by a surface is referred to as its albedo or solar reflectance. Radiative forcing can also be reduced by increasing the thermal emissivity or thermal radiation of materials, which can be understood as the ability of a surface to emit absorbed energy. Both albedo and thermal emissivity are scale factors between 0 and 1 where higher values are correlated with greater capacity to reduce radiative forcing. In existing literature and policy, cool pavements are generally defined by their albedo, while cool roof products are rated using the Solar Reflectance Index, an index that combines albedo and thermal emissivity.

To take advantage of potential reductions in radiative forcing and reap potential co-benefits discussed below, engineers have developed "cool roof" and "cool pavement" technologies that increase the albedo and/or the thermal emissivity of man-made surfaces.

Many cool roof technologies are currently available. Nearly every type of new roof installation, including flat roofs, low sloped roofs, and steep sloped roofs, can be fitted with a new metal or asphalt cool roof material. Existing roofs can be coated, re-covered with a waterproofing surface or replaced. The DOE Guidelines for Selecting Cool Roofs offers a comprehensive picture of the available technologies (DOE, 2010b).

There are several available options for increasing the albedo of pavements. Most approaches involve substituting higher-albedo material into either asphalt concrete or cement concrete. Original alternative paving materials have been developed but are not yet available at a competitive price (EPA, 2008b). A list of currently available paving materials, including their albedo and cost, is provided in Appendix II.

The net effect of cool pavement technologies on radiative forcing is complicated by several factors, and more research is needed on the life cycle climate performance of paving materials. Pavement surface albedo effects on radiative forcing cannot be considered in isolation from other traits of higher-albedo pavements, such as impact on traffic and embedded energy of materials. For instance, existing life cycle analysis indicates that on high-traffic roads with greater heavy-duty vehicle traffic, the effects of road smoothness and stiffness on fuel economy are more powerful determinants of a paving material's global warming impact than the pavement's albedo. For low-traffic roads with less heavy-duty vehicle traffic, surface albedo is more salient (Santero and Horvath, 2009).

4.9.2. Potential impacts

Research by Lawrence Berkeley National Lab (LBNL) estimates that if the albedo of all urban roofs and pavement in the tropical and temperate regions of the world were increased by 0.25 and 0.15 respectively and maintained for 100 years, radiative forcing would be reduced by 24 $GtCO_2eq$ and 20 $GtCO_2eq$, an impact comparable to removing 11 billion car years (Akbari et al., 2010). The methodology used to quantify this impact is explained in Appendix III.

Additionally, cool roofs and cool pavements have significant potential co-benefits. Increasing the albedo and emissivity of a roof reduces air conditioning energy use and associated emissions. An LBNL study finds that if California were to adopt an aggressive cool roofs and pavement policy over 15 years, it could achieve a reduction of 31 Mt CO_2 per year, which is 18 percent of its state-wide climate goals (Akbari et al., 2009). They find that the radiative forcing benefits, in CO_2 equivalent terms, are 10 times greater than the energy saving benefits. Buildings with cool roofs do require additional heating during winter months, but this energy expenditure is generally smaller than the benefits of summer cooling because in the winter the sun is lower, days are shorter, and skies are cloudier (Akbari and Levinson, 2008).

Because of their impact on energy savings, cool roofs have further co-benefits on a private and societal level. Private benefits include reduced cooling energy costs and reduced HVAC equipment costs. Societal co-benefits include fewer blackouts due to reduced peak energy demand, improved air quality due to reduced demand for electricity, and reduced need for new power plant construction (Heinje, 2006).

Cool roofs can also lengthen roof life because they maintain lower temperatures, and some cool roofing materials are more water repellent than traditional roofing materials. These factors can result in cost savings in building maintenance.

Cool roofs and pavements also have the potential to generate significant health co-benefits, primarily by reducing ambient air temperature on hot days. High temperatures can increase the rate of tropospheric ozone formation, which contributes to respiratory illness. Elevated ground temperature also contributes to heat-related illness and death (EPA, 2009c).

In urban areas, cool roofs and pavements reduce the urban heat island effect, the phenomenon of urban areas remaining hotter than surrounding areas. This effect makes residents of urban areas in warm climates particularly vulnerable to heat-related health problems (EPA, 2009). In buildings without air conditioning, cool roofs lower indoor air temperatures, improving occupant comfort.

Increasing the albedo of asphalt concrete pavement yields additional health benefits by reducing the need for new applications of asphalt, which is harmful to workers who inhale asphalt fumes while installing pavement (Santero et al., 2010; NIOSH, 2001).

4.9.3. Current policies and policies under development

There are several policies and green building credit schemes that offer credit for cool roofs, but all of these credits are based on the energy savings from reduced cooling needs; none include the large direct benefits from reducing radiative forcing through increasing albedo.

Several voluntary energy efficiency programs provide credits for cool roofs, including the Energy Star program and the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Green Building Rating System. LEED offers a point toward project certification for high-albedo pavement, but the same credit can also be attained by installing permeable pavement or by providing shade for paved areas (USGBC, 2009).

The widely-used ASHRAE Standard 90.1 and 90.2 for building codes grants cool roofs with energy efficiency credits and also includes them in the prescriptive compliance in some climate zones. The International Energy Conservation Code offers cool roof credits for residential buildings through performance compliance and allows commercial buildings to use the ASHRAE standard that includes the cool roof credit (Akbari and Levinson, 2008). These two standards are the basis of many U.S. state and municipal energy codes.

Some states and cities, including California, Florida, Hawaii, New York City, Atlanta, Chicago and Philadelphia, are developing customized policies for cool roofs. Philadelphia passed a law in May 2010 requiring reflective roofs or green roofs on all new flat or low-sloped buildings (Maynard, 2010).

California now sets an energy efficiency value for cool roofs for all nonresidential and residential buildings, as established under Title 24 of the 2008 Building Energy Efficiency Standard. The prescriptive standard requires cool roofs depending on the slope and density of roofing material, as well as whether it is a new or retrofit project.

There do not appear to be any current policies in the U.S. or internationally that require or provide incentives for high-albedo pavements. Permeable pavements, which allow water to drain through the pavement material, have become a policy priority in some locations for the purpose of stormwater management. For example, California's 2010 green building code requires that a percentage of a home's driveway and other paved surfaces be permeable; the code does not mention pavement albedo, although it does require high-albedo roofs (CBSC, 2010). Permeable pavements have cooler surface temperatures, but their effect on global warming or cooling is not fully understood (EPA, 2008b).

In November 2010, DOE released a draft roadmap for policy and R&D work on cool roofs and pavements. The roadmap focuses on R&D to better quantify the benefits of cool roofs and pavements, as well as policy options to drive more widespread adoption of cool roofs and pavements once greater scientific certainty about costs and benefits is established.

Policies previewed in the DOE roadmap include: (1) further research to quantify the global carbon offset achievable through cool roofs and pavements; (2) the design of model building codes for states in a variety of climates that include provisions for cool roofs and pavements; (3) partnership with the 100 Cool Cities Campaign to support installation of cool roofs in the United States; (4) leverage of bilateral agreements to include technical assistance for cost-benefit analysis of cool roofs, especially with China; and (5) further R&D related to cool pavement technologies, including assessment of life-cycle climate performance.

DOE estimates that the research proposed in the roadmap will take 3-5 years to complete. This report also identifies opportunities for deployment of cool roofs and pavements before the completion of this research, in applications where costs and benefits are sufficiently understood.

4.9.4. Policy opportunities

4.9.4.a. Analysis of the potential scale of cost-effective cool roof deployment through federally funded building construction and roof repairs (*) – The federal government supports building construction, repairs and energy efficiency improvements through a number of programs, including DOE's BetterBuilding best-practices program, DOE's Weatherization Assistance Program, and construction and renovation programs run by the Department of Housing and Urban Development (HUD). Cool roofs could be included more systematically in these programs' guidelines — for example, as a purchasing preference under HUD's construction RFPs. HUD's PowerSavers financing could consider including cool roofs in its performance standards in appropriate regions. Quantifying the potential for cost-effective installation of cool roofs would be a first step toward using these programs to support cool roof deployment. This information gathering would include the number of these units that have flat or low-sloped roofs, as well as the climates in which they are located and how many units regularly undergo roof repairs. This information could be used to calculate the benefits and costs of installing a cool roof when undertaking other federally funded work on a building.

4.9.4.b. Promotion of high-albedo paving material use in applications with an unambiguous climate benefit (*) – Through pilot projects, model codes, and outreach to local governments, agencies could promote cool pavements in applications where research indicates that the reduction in radiative forcing due to the albedo increase is very unlikely to be offset by other factors. One such application would be using high-albedo asphalt rather than conventional asphalt for new parking lots and local roads with low levels of heavy-duty vehicle traffic.

4.9.4.c. Support for adoption of model building codes by state and local governments – Agencies could support early adoption of model building codes in a few high-profile municipalities or state governments. Diversity of partner cities and states could reduce the risk of politicizing this policy. This work could be done through DOE directly or by providing grants to multiple NGOs—such as the American Council for an Energy-Efficient Economy or the White Roof Alliance—to provide this technical assistance and broaden civil society's engagement in this issue.

4.9.4.d. Analysis of cool roof programs as a demand reduction strategy to avoid the need for new power plants – Studies have found highly varied results on peak load reduction from cool roofs, with estimates ranging from 14 to 38 percent peak demand reduction depending on the climate and regional policies (EPA, 2008a). Agencies could perform location-specific analyses for new coal power plant applications to determine the extent to which cool roof programs could reduce the need for increased capacity. This can be done by EPA and/or the DOE State Energy Efficiency Action Network.

4.9.4.e. Addition of cool roofs to the criteria for ranking of state and municipality grant applications for federal funds – States that have more than three months of cooling and have cool roof policies could receive extra points on their applications to the State Energy Program or Energy Efficiency and Conservation Block Grant.

4.9.4.f. Inclusion of cool pavements in the work plan for the Global Superior Energy Performance Partnership – Cool pavements could be included in the work plan for the existing working group on cool roofs within the Global Superior Energy Performance Partnership (GSEP), an international initiative that promotes energy efficiency in commercial buildings and industrial facilities. Pilot projects relating to road or parking lot albedo could be coordinated under this initiative.

4.9.4.g. Establishment of DOE authority to regulate roofing materials via rulemaking or new legislation – DOE sets minimum energy efficiency standards for energy-using appliances and can exercise its authority under the same program by issuing a new rule to set minimum standards for roofing materials. Alternately, new legislation could expand DOE's energy efficiency jurisdiction to include building envelope elements such as roofs. This would enable DOE to implement product labeling and minimum cost-effective solar reflectance standards for cool roofs.

4.9.4.h. Establishment of enhanced financial incentives for cool roof investments – New legislation could provide benefits such as accelerated depreciation tax credits for cool roof investments.

4.9.4.i. Diversification of research institutions funded to research cool roofs and pavements – Most of the existing literature comes from the Heat Island Group at Lawrence Berkeley National Laboratory. A wider set of institutional participation in research could increase understanding and strengthen cool surface policy credibility.

4.9.4.j. Research on potential value of cool roof and cool pavement projects in future carbon markets – Research is needed to understand albedo-based offset protocols for cool roof projects in future carbon markets, specifically the evaluation measures needed for developing countries. Developing this market could potentially fund retrofits in a market-based way that may be quicker and more cost effective than changing building codes.

V. Best Policy Opportunities

5.1 Cross-Cutting Policies

The following opportunities apply across multiple non-CO_2 climate forcers.

5.1.a. Consideration of life cycle emissions

Emissions of non-CO_2 climate forcers are not limited to a section of their use: emissions can occur at various points during the forcers' manufacture, shipment, maintenance, end-use, and/or disposal. A "cradle to grave" life cycle emissions policy would reduce emissions during the entire use of the forcer.

Life cycle climate performance (LCCP) or full fuel cycle analysis, similar to a method being considered by DOE for measuring energy efficiency savings, have been suggested in the literature. The Multilateral Fund, the Montreal Protocol's financial mechanism, has developed a climate impact indicator which it plans to use to evaluate ODS alternatives. For cool paving materials, DOE has already planned to incorporate life cycle analysis. For synthetic chemicals like HFCs, SF_6, PFCs and NF_3 that are used in well-defined sectors and have a limited number of producers, a more comprehensive approach to their reduction would be feasible and useful. For example, a standard for NF_3 use in the solar industry could set emissions targets for NF_3 emissions from solar panels, as well as for its manufacture and shipment. This would allow for greater emissions reductions and enable policy makers to calculate total reductions with more certainty. A case study and further resources about life cycle impacts can be found in Appendix I.

5.1.b. Creation of a task force on non-CO_2 climate forcers in an appropriate international forum

A task force on non-CO_2 climate forcers could provide a forum for countries to make voluntary commitments, share information and take coordinated action. Such a task force could initially focus on addressing black carbon and the high-GWP industrial gases (PFCs, SF_6, and NF_3), as none of these forcers are currently being addressed through other coordinated government efforts and the majority of the production and growth in these forcers is occurring in major economies. Major economies also represent the nations where the technological or policy solutions to address these forcers exist (e.g. the U.S. and EU) or where applying these solutions would have a significant impact (e.g. India and China).

Two possible arenas to catalyze cooperation around non-CO_2 climate forcers could be the Major Economies Forum and/or the Clean Energy Ministerial. In 2009, the Major Economies Forum (MEF), representing 17 of the world's major greenhouse gas emitters, created the Clean Energy Ministerial (CEM), a global forum dedicated to promoting programs and policies that advance clean energy technology, sharing global best practices, and encouraging the transition to a global clean energy economy (CEM, 2010). Within the CEM, a venue like the Global Superior Energy Performance Partnership (GSEP), which focuses on industrial energy efficiency, might be well suited to address emissions from the high-GWP industrial gases. As many high-GWP synthetic gases are heavily used by the semiconductor industry, this initiative could serve as a venue for broad public-private engagement around these gases, in the model of the existing GSEP steel and power working groups. Types of cooperation could include: improving emissions reporting and/or establishing voluntary reporting protocols among countries and industries; R&D in low-GWP gases and production methods; identifying financing for retrofits and system upgrades in CEM/MEF emerging economies; setting voluntary reduction goals; and establishing sectoral caps.The CEM's Clean Energy Solutions Center could also serve as a clearinghouse for countries to share information and best practices on non-CO_2 climate forcers.

There are many other venues where cooperation on non-CO_2 climate forcers could be beneficial; governments will likely have the best sense of where to focus their efforts.

Examples of fact-action opportunities that atask force on non-CO_2 climate forcers could undertake include:

Black Carbon:

- Establishing goals and identify financing opportunities to reduce black carbon emissions from brick kilns
- Cooperating to reduce black carbon emissions that reach the Arctic and the Himalayas, such as increasing the use of more efficient or alternative energy heavy-duty vehicles and maritime vessels in major economies

N_2O:

- Fostering a discussion on global standards and technology sharing pathways for N_2O abatement technologies from nitric acid plants
- Establishing transnational research efforts to monitor and reduce N_2O emissions from agricultural sources

High-GWP industrial gases (PFCs, SF_6, and NF_3):

- Working with the World Semiconductor Council

(WSC), other members of the electronic manufacturing industry, and thin film manufacturers to establish the following for PFCs, SF_6, and NF_3 :

1. Emissions reporting protocols;
2. Best practice sharing for limiting emissions in both end-use and production;
3. Goals for emission reductions from semiconductor and electronic manufacturing; and
4. Research and development on alternative cost-effective technologies that reduce use and/or emissions to enable future reductions.

- Establishing best practice sharing on reducing F-gas emissions from electricity transmission
- Identifying financing for aluminum smelter retrofits in major emerging economies
- Promoting the use of alternative cover gases in magnesium production

All of these potential opportunities for cooperation are discussed in more detail below or elsewhere in this paper.

5.2. Methane

EPA regulation of methane emissions (4.1.4.a)

Under the Clean Air Act, EPA could mandate the reduction or beneficial use of methane emissions from new stationary sources and certain existing facilities. For landfills and coal mines, regulation could encourage the beneficial use of methane and reduce incentives for gas flaring. These regulations could build on existing landfill emissions regulations.

As an example, Alberta has (1) successfully reduced methane flaring at oil production facilities through voluntary and mandatory targets for utilizing the flared methane; (2) set province-wide voluntary targets for productive use of flared methane in the short term (15-25 percent) and the long term (70 percent); (3) instituted a regulatory backstop if voluntary measures fail to provide satisfactory results, including potential withdrawal of production license; and (4) developed a methodology to test the economic feasibility of productive use of flared methane and required that nearby production platforms consider clustering to reduce the infrastructure cost of gas use.

Advantages:

- *High Impact:* Based on EPA's estimates of mitigation costs, the World Resources Institute estimated that it would be possible to reduce annual methane emissions from landfills by 90 $MtCO_2eq$, from coal mines by 44 $MtCO_2eq$, and from oil and gas facilities by 43 $MtCO_2eq$, at a cost of at most \$20 per tCO_2eq (Biano and Litz, 2010).
- *Existing Authority:* Under Section 111 of the Clean Air Act, EPA has the authority to enforce best available control technologies for reducing the emissions of air pollutants — including greenhouse gases — from new installations and installations undergoing significant modification. This regulatory framework allows EPA to require landfills and coal mines to capture methane and either sell it or use it for power generation.
- *Established Technology:* The technology for capturing methane from coal mines and landfills and reducing leakage in gas and oil systems has been demonstrated at significant scale at costs below \$20 per tCO_2eq. Currently, 519 landfills in the United States have been outfitted with landfill-to-energy systems that either sell the gas to the market or use it for power generation (Koch, 2010).
- *Low Cost to Government:* The marginal cost to the government of regulating methane emissions as a GHG under the Clean Air Act could potentially be low given existing monitoring and enforcement protocols. EPA already mandates the reporting of emissions from facilities emitting more than 25,000 tCO_2eq of greenhouse gases, and EPA has since the enactment of the Clean Air Act regulated the emissions of air pollutants and provided guidelines on technologies for emission reduction.
- *Co-Benefits:* Reducing methane emissions would reduce tropospheric ozone levels. A 61 $MtCO_2eq$ reduction of methane per annum would avoid 30,000 premature mortalities in 2030 (West et al., 2010).

Challenges:

- Some projects may face delay in accessing the power grid. If granting access to the grid becomes a condition for granting permission for new construction or significant modification, then landfill and coal mine methane projects may face further delays. As a solution to this problem, the federal government could support state policies to fast-track grid connection for landfill and coal mine methane projects.
- The added cost of reducing methane emissions could create an incentive for operators to rely on minor

modifications to avoid having to build new facilities or significantly expand existing ones.

5.3. N_2O

Establishment of N_2O performance standards under the Clean Air Act (4.2.4.a)

Establishing an industrial standard based on the N_2O emissions rates of the best performing plants would significantly reduce their emissions. This emulates the EU "average best 10 percent" policy for N_2O emissions from nitric acid plants. The EU uses the average emissions of the 10 percent best performing installations in Europe to set a benchmark for a specific sector's emissions cap, which for the nitric acid industry is 1.24 kg N_2O per ton of nitric acid produced (IFA 2010).

Advantages:

- *High Impact:* Bringing all nitric acid plants up to best practices would reduce emissions by 25 $MtCO_2eq$ per year in the U.S. and 100 $MtCO_2eq$ per year worldwide.
- *Existing Authority:* N_2O is both an ODS (ODP of 0.017) and a GHG. Therefore, N_2O could be listed as a Class II substance at the discretion of the EPA Administrator or regulated under Section 615 of the Clean Air Act. Alternatively, N_2O emissions could be regulated as a greenhouse gas under the Clean Air Act, and reductions could be achieved through New Source Performance Standards for nitric and adipic acid plants.
- *Established Technology:* There is a wide variety of abatement technologies available that can reduce N_2O emissions by 80-99 percent. The most promising are the EnviNox process for nitric acid plants and thermal destruction in adipic acid plants. Both processes lead to 98-99 percent reductions in N_2O emissions.
- *Low/Moderate Cost to Private Sector:* Costs are estimated to be approximately \$5 per tCO_2eq for reducing emissions from adipic acid production and \$61 per tCO_2eq for reducing emissions from nitric acid production (Bianco and Litz, 2010), though other cost estimates are much lower than this (EPA, 2006a; Winiwarter, 2005).
- *Low Cost to Government:* A performance standard would apply to the 35 nitric acid plants based in the United States, so these can be easily regulated with minimal staff time.
- *Co-Benefits:* Many N_2O abatement technologies have a co-benefit of reducing NO_x emissions, which is a key constituent of urban air pollution (Seinfeld et al., 1998).
- *Political Feasibility:* Since these performance standards could apply to N_2O regardless of whether it is classified as an ODS or GHG, this measure has particular political appeal. The U.S. has been at the international forefront in setting domestic ODS regulations and supporting the Montreal Protocol, issues that have regularly had bipartisan support.

Challenges:

- There would be costs imposed on nitric acid and adipic acid manufacturers for implementing these new regulations.
- There could be pushback from environmental groups against regulating N_2O as an ODS instead of as a GHG.

Amendment of the Montreal Protocol to include N_2O (4.2.4.b)

The Montreal Protocol is widely considered the most successful international environmental agreement ever negotiated. Not only has it limited the threat of stratospheric ozone depletion, it has delayed the equivalent of a decade of radiative forcing from CO_2. Meanwhile, N_2O is controlled as a greenhouse gas under the UNFCCC Kyoto Protocol, even though it is also the most abundant ozone depleting substance in the atmosphere. The Montreal Protocol taking on N_2O could be a giant contribution to climate change mitigation efforts.

Advantages:

- *High Impact:* Using current technology and existing best practices, the Montreal Protocol could stimulate a 25 percent reduction in N_2O emissions just from fertilizer production and application. This would reduce emissions of over 800 million tons CO_2eq per year if done over a 10-year period.
- *Existing Authority:* Given N_2O's ozone-depleting properties, the Montreal Protocol is completely within its legal purview to control it. Furthermore, the Montreal Protocol has already acted explicitly to deliver a climate co-benefit by accelerating the phase-out of HCFCs

in 2007. And there is now significant support for the North American Proposal to phase-down HFCs (an initiative that would deliver only climate benefits).

- *Established Technology:* The technology for N_2O abatement from nitric acid and adipic acid production already exists and is one the cheapest types of emissions abatement. For fertilizer use, the International Fertilizer Industry Association has indicated that the spread of best practice techniques could reduce N_2O emissions from nitrogen fertilizer by up to 25 percent.
- *Low/Moderate Cost to Private Sector:* As mentioned above, there is already abatement technology on the market and proven best practices that reduce N_2O emissions, reducing potential costs to the private sector. More over, companies in developing countries would be eligible for funding from the Montreal Protocol's financial mechanism, the Multilateral Fund.
- *Low Cost to Government:* The Montreal Protocol's Multilateral Fund has distributed $2.7 billion since its creation in July 1990. Just continuing this rate of funding (equivalent to $135 million per year) could reduce N_2O emissions at a cost of approximately $0.17 per tCO_2eq.
- *Co-Benefits:* Over-use of nitrogen fertilizer can lead to nitrate run-off and eutrophication of fresh-water systems, which can have harmful effects on aquatic ecosystems as well as human health. A reduction in fertilizer use could reduce these impacts. Also, given N_2O's ozone-depleting and climate warming properties, its reduction would have the dual benefit of reducing stratospheric ozone depletion and global warming.
- *Political feasibility:* It is currently unclear how politically feasible transferring N_2O under the Montreal Protocol would be. It would require a new set of experts to be integrated into the Assessment Panels that advise the Parties, the engagement of powerful industries including those that produce and sell nitrogenous fertilizer, and a new round of funding for the Multilateral Fund. None of this is straightforward; however, given the growing possibility that international climate governance will be increasingly decentralized over the coming decades, the Montreal Protocol will have to play a key role in mitigating climate change.

Challenges:

- This ambitious option does have its challenges, with two standing out in particular. The first would be convincing the United Nations Framework Convention on Climate Change (UNFCCC) to let the Montreal Protocol take on the third most important greenhouse gas it controls. The second would be convincing the industries and communities responsible for N_2O emissions (including nitric and adipic acid producers, fertilizer companies, and farmers) that controlling N_2O emissions under the Montreal Protocol is a good idea, both for them and for the environment.

5.4. Black Carbon

Policy support for installation of diesel particulate filters in heavy-duty vehicles (4.3.4.a)

Though U.S. regulations are greatly reducing the PM emissions from new vehicles, older vehicles continue to emit large quantities of black carbon. Focusing on heavy-duty vehicles will have the greatest effect, as these vehicles will burn much more fuel over their lifetime than smaller vehicles. Older vehicles have a shorter remaining lifetime, but they are more likely to be super-emitters. When vehicles are replaced it will be with clean diesel technology. Because most black carbon emissions do not accumulate, the instantaneous climate impact in 2020 would be the same if a 1990 model were replaced in 2020 or if a 1990 model were retrofitted in 2010 and then replaced in 2020; however, the integrated forcing would be much greater in the latter case.

Advantages:

- *Existing Authority:* Initial progress could be made by expanding EPA's Diesel Retrofit Technology Verification program to circulate information on model programs and best practices.
- *Established Technology:* Diesel particulate filters (DPF) can capture over 90 percent of black carbon emissions from vehicles.
- *Significant Impact:* Each vehicle retrofitted with diesel particulate filters will reduce on average approximately 200 kg of black carbon or 125 tCO_2eq (GWP_{100}) over its remaining lifetime (Bond and Sun, 2005). Retrofitting 8,000 heavy-duty vehicles would reduce emissions by approximately 1 $MtCO_2eq$ (GWP_{100}). Black carbon has a lifetime of only a few weeks, so any reduction will have an almost immediate effect.

- *Co-Benefits:* Reducing black carbon emissions will improve air quality and reduce lung-related health problems.

Challenges:

- The cost of retrofitting vehicles with DPFs would be significant, whether paid by the vehicle owners or through a subsidy. The per-ton cost of reducing black carbon emissions through DPFs is projected to be $77 per tCO_2eq (McKinsey, 2010), corresponding to a per-vehicle cost of over $10,000.
- New funding would be needed to provide financial support for retrofits. If regulations were implemented to require the installation of DPFs without government subsidy, they would likely meet opposition from fleet owners and operators and from businesses that rely on heavy-duty vehicles.

International cooperation to address black carbon emissions from brick kilns (4.3.4.b)

Black carbon emissions from this sector are significant and rapidly growing in many developing countries: Kilns and coke ovens are responsible for close to 1 $GtCO_2eq$ of black carbon emissions. There are approximately 300,000 kilns worldwide, and production is concentrated in four countries: China (54 percent), India (11 percent), Pakistan (8 percent) and Bangladesh (4 percent). Because of existing low-cost, low-tech solutions, McKinsey estimates that upgrading kiln technology is a net negative cost abatement option (McKinsey, 2010). Agencies could work to support international cooperation on deployment of mitigation technologies. While the Asian Development Bank has funded some work in this area, and organizations like the Clean Air Initiative have completed case studies, international cooperation could lead to improvements in brick kilns at a scale significant to reduce warming in hot spots like the Himalayas. Such cooperation could take place through an international task force on non-CO_2 climate forcers, as described in Section 5.2.

Advantages:

- *High Impact:* Less than 10 percent of brick kilns globally use modern mechanized technology. Each modernized kiln represents a 2,300 tCO_2eq (GWP_{100}) reduction, and McKinsey predicts that a 300 $MtCO_2eq$ reduction is potentially attainable in this sector (Bond and Sun, 2005, McKinsey, 2010). These numbers are 3.5 times higher using GWP_{20}. In addition, brick kilns are concentrated in black carbon “hot spots,” areas where black carbon emissions have disproportionate impact on the Arctic and the Himalayas.
- *Rapid Sector Growth:* In developing countries, annual production growth rates are high and likely to continue to rise as populations grow and urbanize. For example, in Bangladesh production is increasing by approximately 5.6 percent annually, and in India production is increasing by 5-10 percent annually (Baum, 2010).
- *Established Technology:* Modern brick kilns use 75 percent less fuel and thus produce less black carbon emissions than the most widespread technology.
- *Net Negative Cost to Private Sector:* Modern kilns are more efficient, and McKinsey estimates that upgrading kiln technology is a net negative-cost abatement option (McKinsey, 2010).
- *Co-Benefits:* Reducing black carbon emissions will improve local air quality and reduce respiratory illness.

Challenges:

- The areas where brick kiln emission reduction efforts would be most useful are generally poor rural or semi-rural areas in developing countries or emerging economies. There are likely to be high transaction costs associated with working with communities and manufacturers in these areas.

International cooperation to reduce black carbon emissions that reach “hot spots” (4.3.4.c)

Both the Arctic and the Himalayas are black carbon “hot spots,” meaning that black carbon emissions in these regions have a disproportionate effect on regional warming through positive feedback cycles such as increasing ice albedo. As the Earth warms, activity in the Arctic will continue to rise. Higher levels of exploration, fossil fuel extraction and travel in the Arctic region in coming years will likely dramatically increase transportation (shipping and trucking) in this sensitive region. Regional cooperation will be necessary in order to reduce black carbon emissions in both of these areas. Such cooperation could take place through an international task force on non-CO_2 climate forcers, as described in Section 5.2.

Advantages:

- *High Impact:* Reducing black carbon emissions in these "hot spots" can have significant climate benefits (IPCC, 2007). Furthermore, the Himalayas are also the major source of water for much of Asia. Accelerated melting of the Himalayas could have disastrous effects on the water supply of the region.
- *Existing Authority:* Both the Arctic Council and the Convention on Long-range Transboundary Air Pollution have existing coordination and authority to work together to prevent massive increases in black carbon emissions in the Arctic.
- *Co-Benefits:* Reducing black carbon emissions will improve local air quality and reduce respiratory illness.

Challenges:

- The kinds of cooperation necessary to reduce emissions that affect hot spots can be highly political or challenging to penetrate. For example, reducing emissions from maritime vessels would be very helpful, but bunker fuels are a politically charged international issue. Reducing emissions from heavy-duty vehicles would also be beneficial, but, as discussed in Section 4.3.3 and 4.3.4, challenges such as fuel quality can be serious obstacles to progress.

5.5. Ozone-Depleting Substances

DOE expansion and modification of Cash for Appliances program (4.4.4.a)

Under the Cash for Appliances program, DOE allocated $300 million to states for the provision of consumer rebates for energy-efficient appliance purchases. Key program design elements, including the rebate amount and disposal requirements, were under state purview. As a result, there is a wide range in state requirements of proof of recycling: Some states require requirement of proof of recycling of old equipment, others offer bonuses for submitting proof of recycling, and others do not require proof of recycling (Schultz, 2009).

DOE could expand this program while requiring that states verify the safe disposal of ODS banks. Alternatively, DOE could require that any new rebates only apply to purchases from retailers that are voluntary partners in EPA's Responsible Appliance Disposal program. Currently, only three retailers are partners in the program.

Advantages:

- *High Impact:* An average household refrigerator contains about 1 tCO_2eq of ODS. In 2002, emissions from ODS banks were estimated to be 592 $MtCO_2eq$, but they are expected to decline as the current stock is emitted. By 2015 emissions are projected to be 398 $MtCO_2eq$. The United States accounts for 12 percent of the CFC, 14 percent of the HCFC, and 44 percent of the HFC refrigerant emissions.
- *Fast Acting:* Most ODSs will be released into atmosphere by 2015, so collection and destruction would have to occur in the near term.
- *Established Technology:* Destruction equipment that can destroy 99.99 percent of the refrigerants it processes is already in use at over 100 sites in 26 countries.
- *Moderate Cost to Government:* The estimated cost of ODS removal is \$10-\$35 per tCO_2eq (TEAP, 2009). A program that aimed to reduce 10 percent of the emissions expected in 2015 would cost $398 million to $1.4 billion, depending on the cost of mitigation per tCO_2eq. This does not include additional rebate costs necessary to incentivize the purchase of more efficient appliances.[2]
- *Co-Benefits:* ODS bank destruction would have obvious co-benefits for the ozone layer: end-of-life measures across all sectors have potential cumulative savings of around 300,000 ODP metric tons. These ozone benefits must be accounted for when considering the cost of managing ODS banks, as they will save billions of dollars worldwide in health-care costs associated with skin cancer, eye cataracts, and other ozone-related ailments.

Challenges:

- The source of funding is uncertain.

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[2] Under the Cash-for-Appliances program, rebate values varied across states. In California, the average rebate of $137 was based on the cost of the new appliance (California Cash for Appliances, 2010), whereas in Arkansas, where rebates were of a fixed value by appliance type, the average rebate was $248 (State of Arkansas 2010). These costs are much higher than the $10-35 per unit for collection and recovery of ODS, due to the goal of incentivizing more efficient appliances.

5.6. HFCs

EPA withdrawal of SNAP approval of HFC-134a (4.5.4.a)

Through the SNAP program, EPA could rescind the listing of HFC-134a as an approved alternative to CFCs. Rescinding approval of HFC-134a would force manufacturers to substitute approved alternatives. Table 4.5.1 highlights the alternatives for refrigerants in MVAC systems.

Advantages:

- *Moderate Impact:* Refrigeration and cooling represent the sector with the largest abatement potential for HFCs. McKinsey projects an abatement potential of 0.2 GtCO_2eq. This is due to the high growth expected in HFCs with high GWPs for refrigeration as HCFCs are phased out under the Montreal Protocol.
- *Existing Authority:* EPA has authority to implement this policy through the SNAP program.
- *Established Technology:* Low-GWP alternative HFC-152a is commercially available and SNAP-approved for use in new MVAC systems. HFO-1234yf is in the regulatory process.
- *Low Cost to Private Sector:* Incorporating low-GWP alternatives into motor vehicle air conditioning systems is estimated to cost approximately $4 per t$CO_2$eq (McKinsey, 2010).
- *Political Feasibility:* Similar policies have already been implemented in the European Union and the state of California, and automakers have already signaled their intention to move away from using HFC-134a (GM, 2010).

Challenges:

- The low-GWP alternative HFC-1234yf is not yet an approved CFC alternative under SNAP, and safety and flammability issues for natural refrigerants prevent SNAP approval for large-scale applications. To speed up the approval process, pending SNAP approvals could be prioritized by their climate impact.

EPA and NHTSA incorporation of low-GWP refrigerant credits for medium-duty, heavy-duty, and off-highway vehicle classes (4.5.4.b)

In May 2010, EPA and the Department of Transportation set new fuel economy rules and GHG emissions standards for light duty vehicles, which includes HFCs from mobile air conditioning. These standards have not yet been applied to other vehicle classes.

Advantages:

- *Moderate Impact:* HFC emissions from motor vehicle air conditioning totaled 50.7 tCO_2eq in 2008 (EPA, 2009c).
- *Rapid Sector Growth:* High growth is expected in high-GWP HFCs domestically and abroad as HCFCs are phased out under the Montreal Protocol (see Appendix I).
- *Existing Authority:* EPA and the Department of Transportation have the authority to set fuel economy and GHG emissions standards for all vehicle classes.
- *Low Cost to Private Sector:* Incorporating low-GWP alternatives into motor vehicle air conditioning systems is estimated to cost approximately $4 per t$CO_2$eq (McKinsey, 2010).
- *Established Technology:* The low-GWP alternative HFC-152a is commercially available and SNAP-approved for use in new MVAC systems. HFO-1234yf is in the regulatory process.

Challenges:

- HFC-1234yf is not yet an approved CFC alternative under SNAP.

Engagement with large commercial cooling and retail food refrigeration industries to reduce HFC leakage in existing and new equipment (4.5.4.c)

Refrigeration and cooling represents the sector with the largest abatement potential for HFCs. Agencies could engage suppliers, installers, and purchasers of cooling and refrigeration equipment to promote available technologies for leakage reduction, such as secondary loop or distributed systems with a smaller charge size of coolants.

Advantages:

- *Moderate Impact:* McKinsey projects an abatement potential of 0.3 $GtCO_2eq$. This is due to the high growth expected in HFCs with high GWPs for refrigeration as HCFCs are phased out under the Montreal Protocol.

- *Existing Authority:* This policy could build on EPA's existing work promoting leakage reduction in supermarkets through the Greenchill partnership, and could also connect to existing DOE work on energy efficiency in commercial buildings and industrial facilities.
- *Established Technology:* Secondary loop and distributed systems technology are readily available (see Appendix II).
- *Net Negative Cost to Private Sector:* Reduced leakage diminishes the need for refrigerant recharging. McKinsey estimates a savings of \$6 per tCO_2eq and \$1 per tCO_2eq for large and retail food refrigeration, respectively (McKinsey, 2010).

Challenges:

- New federal funding for energy efficiency programs is likely to be very limited in coming years. Perhaps DOE could partner with individual states to seek appropriate funding, or work with the Consortium for Energy Efficiency to address commercial-scale HFC leakage.

5.7. PFCs

International cooperation to identify financing for aluminum smelter retrofits (4.6.4.a)

Because the primary hurdle to retrofit investment is upfront capital costs, international cooperation could help identify funding mechanisms for countries where new technology uptake is low. Retrofits will save companies money through increased efficiency, creating a situation where they could repay a retrofit loan using cost savings from efficiency. International cooperation in this area could also facilitate discussions around setting global voluntary standards for PFC emissions from aluminum manufacturing and help pinpoint other areas ripe for international cooperation as technology and aluminum demand evolves. Such cooperation could take place through an international task force on non-CO_2 climate forcers, as described in Section 5.2.

Advantages:

- *Moderate Impact:* Plants employing best practices emit one-tenth the PFCs of the median plant. Bringing all plants worldwide up to best practice would reduce PFC emissions by 63 $MtCO_2eq$ each year.
- *Established Technology:* The technology to retrofit existing plants is relatively inexpensive and well-established.
- *Co-Benefits:* Retrofitting plants also makes them more efficient, resulting in cost savings for companies and reductions in CO_2 emissions.

Challenges:

- Without some form of incentive or loan-financing program, investment in retrofits is unlikely. At the same time, there are many demands for international funding to mitigate climate change. As suggested above, employing a mechanism wherein cost savings from increased efficiency are used to repay a loan for the initial retrofit cost could overcome this challenge.

International cooperation to reduce PFC emissions from electronics and semiconductor manufacturing (4.6.4.b)

The electronics and semiconductor industries are relatively new, and while PFC emissions from these industries are now small, they have high growth rates and are extremely long-lived. There is a clear need for leadership from governments to engage international industry organizations like the World Semiconductor Council and International SEMARTECH to tackle the use and release of PFC emissions. Such cooperation could initially provide a forum to promote more comprehensive industry PFC emission reporting and to share information and best practices regarding technology and policy options to reduce PFC emissions from semiconductor and electronics manufacturing. Initiating this kind of dialogue is the first step in working to reduce emissions from this sector, and establishing cooperation now could limit the current upward trend in PFC emissions. Such cooperation could take place through an international task force on non-CO_2 climate forcers, as described in Section 5.2, and could also address SF_6 and NF_3.

Advantages:

- *Moderate Impact:* If all semiconductor manufacturers used post-use destruction technology, PFC emissions would be reduced by 0.1 $GtCO_2eq$ per year.
- *Established Technology:* Post-use destruction technology exists that can reduce emissions over 95 percent.
- *Political Feasibility:* In previous work with EPA, the semiconductor industry has expressed interest in collaborating to reduce emissions from its sector.

Challenges:

- There is currently no international governmental cooperation in this area. Because the first step to establishing such cooperation would be to open a dialogue among governments and manufacturers, we cannot calculate an impact in terms of emission reductions.

5.8. Roof and Pavement Reflective and Emissive Properties

Cool Roofs

Analysis of the potential scale of cost-effective cool roof deployment through federally funded building construction and roof repairs (4.9.4.a)

The federal government supports building construction, repairs, and energy efficiency improvements through a number of programs, including DOE's BetterBuilding best-practices program, DOE's Weatherization Assistance Program, and buildings managed under the Department of Housing and Urban Development (HUD). Cool roofs could be included more systematically in these programs' guidelines—for example, as a purchasing preference under HUD's construction RFPs.

Quantifying the potential for cost-effective installation of cool roofs would be a first step toward using these programs to support cool roof deployment. This information gathering would include the number of these units that have flat or low-sloped roofs, as well as the climates in which they are located and how many units regularly undergo roof repairs. This information could be used to calculate the benefits and costs of installing a cool roof (for example, a waterproof cool roof membrane) when undertaking other federally funded work on a building.

Advantages:

- *Existing Authority:* While most roof installations fall under local and state building code jurisdiction, federally funded construction projects constitute one of the few areas where the federal government has direct authority over roofs. Cool roofs could be added as a purchasing priority or preference under HUD's construction RFPs. Effort should be made to share information about the benefits of cool roofs with local housing authorities as well as with centralized offices at HUD, since the housing authorities have a great deal of latitude in establishing contract terms. This work could begin under the existing MOU between EPA, DOE, and HUD, in connection with HUD's energy efficiency goals.
- *Established Technology:* Cool roof materials are well-established for most roofing materials and are rated by the Cool Roof Rating Council.
- *Low Cost to Government:* In many cases, cool roof materials are available at no additional cost over traditional roofing materials. Labor makes up the largest portion of cool roof installation costs, so in projects where the government is already funding a roof installation or replacement, the additional costs of installing a cool roof may be low. Government costs could be split with the private sector if HUD decided to integrate cool roofs within the overall RFP process such that contractors bidding would take on some or all of the costs.
- *Low Cost to Private Sector:* There is no cost to the private sector if this policy is implemented with government funds. If the policy were designed such that private-sector firms shared the cost of cool roof installations, the marginal cost of installing a cool roof would be low for projects already involving roof installation.
- *Co-Benefits:* Health co-benefits arise from the reduction of smog and the heat island effect in urban areas (EPA, 2009c). Furthermore, cool roofs may prolong the lifetime of the roof and can reduce electricity consumption from air conditioning leading to cost savings, reduced CO_2 emissions, and reduced peak demand on the electric grid.

Challenges:

- *Low to moderate impact:* Each square meter that a surface's albedo is increased by 0.25 results in a global radiative forcing change of 6.2×10^{-14} W/m^2. Thus for an average roof, with a lifetime of 20 years the CO_2eq saved is 1.5 tCO_2eq using GWP_{100} (assuming the roof went back to being dark after the 20 years), or 5.25 tCO_2eq using GWP20. If the deployment of cool roofs through federal housing programs led to the installation of cool roofs that increase albedo by 0.25 on 50,000 homes, each with 100 square meters of roof area[3], it would reduce the equivalent of 75 $ktCO_2$eq. The methodology used to quantify this impact is explained in Appendix IV.

- Labor costs make up most of the cost of cool roof installation, and cool roof installation is unlikely to be cost-effective in projects that do not otherwise require roof work.

Cool Pavements

Promotion of high-albedo paving material use in applications with an unambiguous climate benefit (4.9.4.b)

There are major outstanding questions about the life cycle climate impacts of paving materials in most applications, and ongoing R&D outlined in DOE's Cool Roofs Roadmap will help resolve these questions. However, there are some applications where research indicates that the reduction in radiative forcing due to the albedo increase is very unlikely to be offset by other factors—for example, using asphalt concrete with high-albedo aggregate or with a high-albedo chip seal, rather than conventional asphalt concrete, on surfaces with low heavy-duty vehicle traffic and where the pavement is new or due to be replaced. Through pilot projects, model codes, and collaboration with local governments and voluntary standards organizations, DOE could promote cool pavements in these applications without waiting for further R&D.

Advantages:

- *Existing Authority:* DOE could write model regulations to be incorporated in state and local building codes and could work with the U.S. Green Building Council to encourage the inclusion of more detailed pavement albedo requirements in the LEED certification program or in other voluntary codes.
- *Established Technology:* Higher albedo paving materials are commercially available, including cement concrete with high slag content and asphalt concrete with light-colored aggregate or chip seals. No behavioral change is required beyond the initial choice of paving material. More detail on currently available paving materials is included in Appendix II.
- *Low Cost to Government:* This policy could be implemented at minimal cost to the government; the only cost would be developing model regulations and disseminating them among state and local governments and green building organizations.
- *Low Cost to Private Sector:* The cost of asphalt with high-albedo aggregate is comparable to the cost of traditional asphalt. Asphalt pavement with high-albedo aggregate can produce cost savings due to reduced maintenance costs (Ting et al., 2001). More detail on technology and costs is included in Appendix II.
- *Co-benefits:* Health co-benefits exist from reduced need for new applications of asphalt, as well as from reduction of the heat island effect in urban areas (Santero et al., 2010). Reductions in CO_2 emissions and maintenance costs are also possible from reduced maintenance needs associated with cool pavement materials.

Challenges:

- *Low to moderate impact:* Each square meter that a surface's albedo is increased by 0.1 results in a global radiative forcing change of 2.5×10^{-14} W/m^2. Using light-colored aggregate in asphalt concrete increases solar reflectance by 10 percentage points and produces a one-time offset of 6 $kgCO_2e$ per square meter (assuming it stays this color for 100 years; see Appendix III). The total potential impact depends on take-up rate and total affected area. A pilot program involving paving 200 lane-miles of local roads (approximately 980,000 square meters) with light-aggregate asphalt would produce an offset of 5,900 tCO_2eq — the equivalent of taking 1,100 cars off the road for one year (EPA, 2005). A pilot program covering 10 large parking lots would cover the same area and produce a similar offset. More detail on technology and costs is included in Appendix II. While this initiative can be piloted under existing programs, scaling it up would be more difficult. Deploying high-albedo roads or parking lots at scale would require action by the many state and local governments with responsibility for road paving and building codes.

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[3] 50,000 units represents 1 percent of the 5 million units that HUD helps fund or 50 percent of the 100,000 homes annually funded through the Weatherization Assistance Program prior to the program's temporary expansion under the Recovery Act.

VI. Conclusion

This report lays out what the authors believe to be some of the best options for mitigating a suite of non-CO_2 climate forcers. As a companion to these options, we present a scientific overview of the most important non-CO_2 atmospheric warming agents, including historical emissions, current policies, and an important discussion of the various metrics that can be used to measure their potency. Nearly all the top policy options come under existing authority (either domestic or international), could be implemented in the near term, and would result in considerable CO_2-equivalent reductions with low to moderate cost.

As mentioned at the outset, these options should in no way be interpreted as alternatives to action on CO_2. Given the small and shrinking window of opportunity we have to deal with climate change, there must be fast and meaningful reductions in CO_2 emissions, driven by strong domestic and international policies. The aim of this report is to highlight important mitigation opportunities for non-CO_2 climate forcers to complement strong action on CO_2, which could be a vital buffer in avoiding the worst effects of climate change.

Summary of Best Policy Options for Non-CO_2 Climate Forcers

Forcer	Policy Options	High Impact	Low Cost	Quick Implementation	Co-Benefits
Cross-Cutting Policies	Consideration of life cycle emissions	✓	✓		✓
	Creation of a task force on non-CO_2 climate forcers in an appropriate international forum	✓	✓	✓	✓
Methane	EPA regulation of landfill and coal mine methane emissions	✓	✓	✓	✓
N_2O	Establish N_2O performance standards under the Clean Air Act	✓	✓	✓	✓
Black Carbon	Continued support of retrofit projects with a focus on heavy duty vehicles of model year 1998-2009	✓		✓	✓
	International cooperation to address black carbon emissions from brick kilns	✓	✓	✓	✓
	International cooperation to reduce black carbon emissions that reach "hot spots"	✓		✓	✓
ODS Banks	DOE expansion and modification of Cash for Appliances program	✓		✓	✓
HFCs	EPA withdrawal of SNAP approval of HFC-134a		✓	✓	
	EPA and NHTSA incorporation of low-GWP refrigerant credits in medium duty, heavy duty, and off-highway vehicle classes		✓	✓	
	Engagement with large commercial cooling and retail food refrigeration industries to reduce HFC leakage in existing and new equipment		✓	✓	
PFCs	International cooperation to identify financing mechanisms for aluminum smelter retrofits		✓	✓	✓
	International cooperation to reduce PFC emissions from electronics and semiconductor manufacturing			✓	
Cool Roofs and Pavements	Analysis of the potential scale of cost-effective cool roof deployment through federally funded building construction and roof repairs		✓	✓	✓
	Promotion of high-albedo paving material use for local roads with low traffic		✓	✓	✓

Appendix I: Case Studies

Life Cycle Emissions: The Case of the NF_3 LCA

The need for life cycle analysis has been expressed by many, including the IPCC, which has begun a meta-analysis of sector-specific LCAs. To illustrate the need for LCA we can look at a 2010 paper by Fthenakis et al. that is the first study to quantify the life-cycle emissions of NF_3 in photovoltaic (PV) manufacturing on the basis of measurements collected during the manufacturing and end-use processes. According to their results, PV manufacturing plants emit only 0.1 percent of the NF_3 they use, while companies that manufacture NF_3 release 1-3 percent during its production and shipment. Thus, for average U.S. solar irradiation conditions (1,800 kWh/m2/year), the emissions from using NF_3 add 2-7gCO_2eq/kWh. This can be offset within the first one to four months of the PV equipment lifetime.

These figures are significantly less than the 16 percent emission rate estimated by Prather et al. (2008). However, the PV industry is relatively young and therefore has more efficient systems than many other industries, so their usage accounts for only about 3 percent of global NF_3 production. Indeed, the authors estimate that total NF_3 emissions in 2008 represented 9 percent of production, implying worse practices than the PV industry. Nevertheless, the issue of life cycle emissions raised in this paper deserves attention in other areas of NF_3 use, as well as for other potent synthetic greenhouse gases.

Black Carbon: Diesel Retrofit Programs in California and New York City

California has instituted several diesel replacement and retrofit programs since 2000. A high profile example has been the Low Emission School Bus Program. Between 2000 and 2005, $70 million was allocated to purchase 400 new buses and add over 3,000 filters on existing vehicles. Even so, a Union of Concerned Scientists report in 2006 cited California's school bus fleet of 30,000 vehicles as one of the worst in the country. At the time, about 300 of the buses were built before 1977, and the average bus emitted two times the amount of particulate matter per mile as a big rig. The state allocated $200 million to replace and retrofit vehicles. In 2009, funding for the program was suspended due to the state budget crisis. California potentially paid three times too much for retrofits due to a lack of competition among vendors, according to Axel Friedrich, former head of the Transportation Department in the German Federal Environmental Agency. In another approach, the New York City Private Fleet Diesel Retrofit Program was announced by a partnership of the New York State Energy Research and Development Authority and the New York City Department of Transportation. This program will fund up to 80 percent of the cost of diesel retrofit projects for private sector heavy-duty vehicles, up to a total of $2.4 million.

Resources for Further Information:

- The Union of Concerned Scientists' report about California's diesel incentive retrofit costs and benefits can be found at the organization's website: www.ucsusa.org/clean_vehicles/solutions/cleaner_diesel/california-diesel-incentive.html.
- New York City's diesel retrofit program is described on the website of the New York State Energy Research and Development Authority: www.nyserda.org/funding/2058summary.pdf .

ODSs: Refrigerant Reclaim Australia

Since 1993, Refrigerant Reclaim Australia has collected taxes from imported F-gases to provide rebates for ODS bank removal. With a tax of 1 AUD per kilogram, they collected AUD 1.3 million that were offered as rebates as of 2006. This collection service has prevented the emission of approximately 10 MtCO_2eq. In 2003, recovery of HFCs and PFCs were included in the list of recovered F-gases. The program's success earned it the Climate Protection Award from the U.S. EPA in 2006 for its efforts in destroying ODSs and protecting the ozone layer and climate. According to Steve Anderson, Executive Director of Refrigerants Australia, this initiative may be too difficult for the U.S. to emulate due to the involvement of more industry players in the U.S. F-gas market. However, further investigation is needed to determine a similar program's appropriateness for the U.S.

Resources for Further Information:

- More information about the co-regulatory model of the industry-based non-profit Refrigerant Reclaim Australia can be found at the program's website: www.refrigerantreclaim.com.au.

HFCs: Coca-Cola goes HFC-free

In a partnership with UNEP, Greenpeace, and Refrigerants, Naturally!, Coca-Cola has committed to going HFC-free in all new vending machines and coolers by 2015 to reduce their climate footprint. As of December 2009, Coca-Cola had 85,000 coolers and vending machines using CO_2 as a refrigerant. With this new fleet of refrigerators, Coca-Cola has observed energy savings between 7-75 percent depending on the equipment. As a large multinational corporation, Coca-Cola has great market power to encourage technology transfer to natural refrigerants. Equipment failure has been well below the rates of equivalent equipment running on HFC-134a. The equipment failure has largely been due to quality and peripheral device issues, not the CO_2 circuit. Manufacturers have performed successful reliability tests in the laboratory and have observed very few failures.

Resources for Further Information:

- Refrigerants, Naturally! is a global initiative of companies committed to combat climate change and ozone layer depletion by substituting harmful fluorinated gases with natural refrigerants. www.refrigerantsnaturally.com.
- Beyond HFC is an industry-backed campaign to replace HFCs with natural refrigerants. They released a technical response paper to the May 2010 assessment of HCFC replacements conducted by the Montreal Protocol's Technical and Economic Assessment Panel (TEAP). This report can be found here: www.unep.ch/ozone/Meeting_Documents/oewg/30oewg/conf-ngos/Beyond%20HFCs%20position%20on%202010%20TEAP%20report.pdf

HFCs: Expanding Montreal Protocol For Chemical Phase-out

The Montreal Protocol can be a powerful vehicle for eliminating HFCs given its track record phasing down other ozone-depleting substances (ODS). Beginning with an international consensus to control ODSs with the signing of the Montreal Protocol in 1987, the 196 countries party to the treaty made a strong commitment to repair the damage that CFCs inflicted on the ozone layer. With the implementation of the Montreal Protocol in 1989, developed countries began an increasingly rapid phase-out of the controlled chemicals, while developing countries phased out consumption following a ten-year grace period. Also benefiting developing countries was the Multilateral Fund, a fund designed to cover incremental costs to developing countries of the ODS phase-out.

The scheduled phase-out of these ODS compelled the development of HCFCs, the next generation of refrigerants. While the ODPs of HCFCs were less than CFCs, they still posed a threat to the ozone layer and were later incorporated into the Montreal Protocol for a similarly structured phase-out. Importantly, developing countries phased-down production of CFCs and HCFCs ahead of schedule. Accordingly, the Montreal Protocol added an amendment in 2007 to accelerate HCFC reductions.

The "start and strengthen" approach taken by the Montreal Protocol has long been heralded as a primary reason for its success, as have the transparency and freedom of the Technology and Economic Assessment Panels (TEAP), which bring together industry experts to collaborate, develop and report feasible alternative technologies. The past success of the Montreal Protocol serves as a valuable example of a successful international environmental treaty that spurred development of alternatives for all sectors.

Resources for Further Information:

- The Institute for Governance and Sustainable Development's argument for phasing down HFCs through the Montreal Protocol can be viewed at the organization's website: www.igsd.org/montreal/documents/IGSDHFC2010OnePager.pdf
- UNEP's report titled, " A success in the making: The Montreal Protocol on substances that deplete the ozone layer" is available at its website: http://ozone.unep.org/Publications/MP_A_Success_in_the_making-E.pdf

PFCs: Case Study: Brazil's Aluminum Can Recycling Program

It is often hard to recycle a product that is widely distributed in small quantities, in contrast to recycling aluminum from buildings and cars. Despite this challenges, Brazil and other countries have developed strong aluminum can recycling programs, with Brazil leading the world with a recycling rate of 96.5 percent of its aluminum cans. How has this been achieved? According to Henio de Nicola, recycling coordinator for the Brazilian Aluminum Association (ABAL), Brazil's program is set up like a strategy for winning a soccer game. First, a strong defense is set up in the form of a structured processing chain. Instead of the government paying a subsidy for recycling, revenue from the value of the aluminum itself is accrued to recycling participants. Second, this is accompanied by a mid-field of social programs and environmental education. Third, there are “strikers”—over 180,000 Brazilians who collect cans daily all over the country. The Brazilian example is evidence that a simple well-designed plan and processing chain, coupled with strong public education efforts, can yield strong results for increasing aluminum recycling and thereby reducing PFC emissions.

Resources for Further Information:

- Industry article on “Emerging Trends in Aluminum Recycling: Reasons and Responses” from SK Das - Metals, Minerals and Materials Society (TMS) meeting, 2006. www.engr.uky.edu/pdf_docs/cat/DrDas-TMS2006-Emergingtrendsinaluminumrecycling.pdf
- Research on policy and socio-economic factors surrounding aluminum recycling titled “Border scavenging: a case study of aluminum recycling in Laredo, TX and Nuevo Laredo, Mexico” by Martin Medina, Resources, Conservation and Recycling, Aug. 1998.

Appendix II: Mitigation Technology Options and Costs

This appendix lists the primary technologies that can replace the need for climate-damaging gases and forcers, along with the cost information when it was available. EPA's assessment of abatement technologies (EPA, 2006a) is the primary source of information, and it is augmented by updated research.

Methane: Technologies for reducing methane emissions

Review of existing and operationally proven technologies

Waste: The anaerobic decomposition of municipal solid waste generates methane from landfills. Through the selective collection and recycling of waste, the organic content in landfills can be reduced and methane emissions from solid waste avoided. Landfill gas-to-energy projects collect the methane from landfills through a network of vertical wells, gathering pipelines, pumps, and compressors. The methane may be flared onsite or used for power generation in a turbine, engine, or boiler.

The capital costs of a project include the wells, wellheads, gathering pipelines, dehydrators, and the power generator or pipeline to the natural gas grid if the methane is sold to the grid. Annual costs include labor, maintenance, and monitoring costs. All equipments are in use in commercial-scale landfill-to-gas projects around the world. Key factors that drive methane emissions from landfills, as well as the costs of capture, include (a) the quantity of waste, (b) the composition of waste (mainly the organic content) and (c) the type of landfill. EPA estimates that landfill-to-energy projects break even between -\$16.70 (i.e. a net savings of \$16.70) and \$73.02 per tCO_2eq, depending on the end-use of the methane (EPA, 2006a).

Components of waste LFG systems:

- Collection and flaring system
  - Wells; wellheads and gathering pipeline system; knockout, blower, and flare
- Utilization pumping system
  - Skid mounted filter; compressor; dehydrator unit; pipeline
- Turbine for power generation
  - Turbine; engine; boiler

Coal-mine methane: Methane forms in coal seams through the decomposition of organic materials. During mining operations, gases exit the fractured seams to the atmosphere through the mine shaft. In concentrations of 5-15 percent, methane is flammable and poses a safety risks in underground mines. Operators mitigate this risk by injecting air into the mine shaft to reduce methane content to less than 1 percent, and the resulting air-methane mix is then released to the atmosphere. Through drilling vertical wells, gob wells or horizontal wells into the seams, mines can capture the methane prior to operation and thereby reduce the need for ventilation while also capturing gas for power generation. Through this "degasification" process, operators may capture methane in 30-90 percent concentration. Key factors that drive the amount of methane captured include (a) the depth of the seam (the deeper the seam, the higher the methane content), (b) permeability and porosity of deposits, and (c) the type of mining used to extract the coal. In general, roughly 57 percent of the gas recovered through degasification may be supplied directly into the natural gas grid.

Operators can choose to remove impurities in the gas drawn off the wells and increase methane recovery rates beyond degasification. At most mines, this would mainly entail installing a Nitrogen Removal Unit and/or a dehydrator. Degasification and enhanced degasification projects have a break-even cost ranging from \$-11.66 to \$19.80 per tCO_2eq depending on the end-use of the methane (EPA, 2006a).

The methane diluted with air in mine shafts can also be oxidized and used for heat or electricity generation. The capture and separation of this methane is prohibitively expensive given the low concentration of the gas. Catalytic oxidation projects in the U.S. break even at a price of \$14.36 per tCO_2eq, assuming a 10 percent discount rate (EPA, 2006a).

The equipment of a degasification system includes filters, compressors, dehydrators, gathering pipelines systems and the power generation unit which may have a turbine, engine, and/or a boiler. Wells are drilled as the mine expands its operation and therefore represent on ongoing capital expenditure as opposed to a one-time cost.

Components of degasification systems:

- Collection and flaring system
  - Wells; wellheads and gathering pipeline system; knockout, blower, and flare
- Utilization pumping system

  - Skid mounted filter; compressor; dehydrator unit; pipeline
- Turbine for power generation
  - Turbine; engine; boiler

Oil and gas: Methane is produced, treated and transmitted in large quantities in the oil and natural gas sectors. Oil platforms can vent or flare the methane, capture it for power generation, or send it to the pipeline for distribution. The natural gas sector emits large quantities of methane mainly from leaking pipelines, valves, pumps, and compressors that treat high-pressure gas. Direct inspection and maintenance can detect and replace worn parts and seal leaking pipes. As methane is a colorless and odorless gas, leakage in an extensive and complex gas infrastructure is often challenging to detect. However, infra-red cameras have the potential to increase methane detection rates significantly. High-bleed pneumatic devices control pressure through releasing methane. These devices can be replaced with more efficient alternatives that achieve similar pressure control but with less leakage. Break-even costs vary significantly. However, EPA estimates that 53 percent of emissions can be avoided at costs less than \$60 per tCO_2eq (EPA, 2006a).

N_2O: Alternatives

The U.S. uses non-selective catalytic reduction techniques (NSCR) and selective catalytic reduction techniques (SCR) to reduce N_2O to molecular nitrogen (N_2). NSCR is more effective but generally not preferred in today's plants because of high energy costs and associated high gas temperatures. Approximately 17 percent of nitric acid plants in the U.S. are equipped with NSCR, representing 7.6 percent of estimated national production (EPA, 2010a). The total capital cost for this option is \$6.27 per tCO_2eq. In the U.S., the operation and monitoring cost is estimated at \$0.16 per tCO_2eq. NSCR has a technical lifetime of 20 years, yielding a break-even price of approximately \$1.90 per tCO_2eq (EPA, 2006a).

IIASA (2005) calculates the European abatement costs of N_2O from adipic acid plants to be \$0.19 per tCO_2eq, and \$0.55 for nitric acid plants (using a 2005 transfer rate). Both EPA and IIASA estimates are significantly below current carbon prices, with the EU Emissions Trading Scheme trading at \$19.84 per tCO_2eq abated in December 2010.

One of the most successful abatement technologies is known as the EnviNOx process, which achieves a removal rates of 98-99 percent, with an added co-benefit of reducing NO_x emissions (a major precursor to urban air pollution) to as low as 1 ppmv. The EU has declared the EnviNOx process to be the best available technique for N_2O and NO_x abatement in nitric acid plants (Wiesen, 2010).

Abatement technologies include catalytic decomposition and thermal destruction, which leads also to the production of NO, but can be recovered as nitric acid. Total capital costs for thermal destruction are \$0.38 per tCO_2eq. In the United States, O&M costs are estimated to be approximately \$0.16 per tCO_2eq. This abatement option has a technical lifetime of 20 years, yielding a break-even price of approximately \$0.27 per tCO_2eq (EPA, 2006a).

ODSs: Technologies for destroying ODS banks

The UNEP-approved destruction technologies with 99.9 percent destruction and removal efficiencies are:

- Cement kilns
- Liquid injection incineration
- Gaseous fume oxidation
- Municipal solid waste incineration
- Reactor cracking
- Rotary kiln incineration
- Argon plasma arc
- Inductively coupled radio frequency plasma
- Microwave plasma
- Nitrogen plasma arc
- Gas phase catalytic dehalogenation
- Superheated steam reactor

HFCs: Alternatives

Several of the most attractive policy opportunities to regulate HFCs employ a transition from high-GWP HFCs to lower-GWP alternatives. Within each sector, the abatement opportunity varies along with the associated costs.

When considering the sector-specific abatement potentials and technology options, the refrigeration and air conditioning sectors offer the greatest abatement potential. In these sectors, high-GWP HFCs can be replaced with low-GWP HFCs, ammonia, or CO_2. Alternatively, a secondary loop system can reduce leakage and refrigerant charge size. In these sectors, there are 550 $MtCO_2eq$ in abatement potential at zero or negative cost (McKinsey, 2010).

In the solvent sector, high-GWP HFC solvents can be retrofitted with low-GWP HFCs or HFE-7100 and HFE-7200. By 2020, this could reduce solvent emissions by 36 percent in the United States. Besides administering the transition, this has no additional cost (EPA, 2006a).

Blowing agents used in the foam sector can be replaced with low-GWP alternatives, hydrocarbons, or CO_2. A few of the low-GWP alternatives are XPS boardstock, PU spray, PU one-component from HFC-134a, and from HFC-152a, which all have negative costs and respective abatement potentials of 2.49, 1.59, 0.48, and 0.06 $MtCO_2eq$ (EPA, 2006a).

In the aerosol sector, non-medical dose inhaler applications can transition to hydrocarbons, not-in-kind technologies, or HFC-152a. These options have negative associated costs and abatement potentials of 3.95. 3.95, and 14.64 $MtCO_2eq$, respectively (EPA, 2006a).

The unwanted HFC-23 produced as a byproduct of HCFC-22 production could be collected and destroyed by thermal oxidation. This has an abatement potential of 24 $MtCO_2eq$ with a cost of $4 per tCO_2eq (McKinsey, 2010).

Initiatives by individual corporations demonstrate the capacity of some of these alternatives:

- General Motors committed to using low-GWP alternative HFO-1234yf in all new models by 2013 (Feldman, 2010; GM, 2010).
- A pilot program with Ben and Jerry's introduced the first 2,000 freezers with hydrocarbons to the United States. Outside this program, hydrocarbons are not yet SNAP-approved for this end use (Greenpeace, 2009).
- Low-GWP alternatives and natural refrigerants are pending approval under the EPA SNAP program.

PFCs: Alternatives For the Semiconductor and Electronics Manufacturing

The following strategies for PFC reduction are for the electronics industries.

Recycling/Recovery: Demonstrations prove that greater than 99 percent recovery can be achieved. However, uptake of recycling has been low. This is largely because of the prohibitive costs of technologies like cryogenic condensation and membrane separation that would allow for recycling and recovery (Chang and Chang, 2006). There may also be an industry bias against recycling as virgin materials are preferred to ensure uncontaminated inputs.

Abatement: There are three major available technologies for reducing PFC emissions: plasma processing, thermal/chemical oxidation, and combustion.

> Plasma processing: Non-thermal plasma technology (NPT) has been a promising avenue of research because of its high reaction rate and lower power consumption than other strategies. After a full assessment of different abatement options, Chang and Chang (2006) argue that NTP combined with a catalyst or absorbent "has a good potential to be used as an integrated technology for abating PFCs from the complicated gas streams of semiconductor industries." In particular, they find the most promising option is NTP processing operated at atmospheric pressure (simulated using a dielectric barrier discharge) with a catalyst or adsorbent.
>
> Progress made in this area has resulted in PFC removal efficiencies of more than 98 percent using conventional plasma-resolution-type abatement systems. In particular, low pressure plasma resolution PFC abatement technologies are often compact, low cost, and have a PFC removal efficiency of approximately 98 percent. This method uses a cylindrical inductively coupled plasma (ICP) chamber. Suzuki et al. suggest a slight improvement on this strategy that immobilizes the PFCs decomposed by a 2 MHz IPC plasma and then recombines it at a low pressure using Ca(OH)2/CaO. This system can have a removal efficiency of over 99 percent (Suzuki et.al., 2009). EPA estimates the cost for plasma abatement, assuming a 95 percent emission reduction efficiency, to be $35,000 in capital costs per etching chamber plus $1,000 per chamber in annual operational expenses. No cost savings are reported from this process.
>
> Thermal/chemical oxidation: Thermal processing units (TPUs) do not affect the manufacturing process and can be used to reduce PFC emissions from both etching and the chemical vapor decompression chamber cleaning processes. Costs, however, are high for the fuels and solution necessary for scrubbing byproducts like HF. Furthermore, they produce NO_x (EPA, 2006a). EPA estimates TPU costs, assuming a 97 percent emission reduction efficiency, are around

$189,850 in capital costs per four etching chambers and around $11,000 per every four etching chambers in annual operations. No cost savings are associated with this technology.

Combustion/Catalytic Decomposition System: While specific combustor systems can achieve greater than 90 percent in reduction efficiency for C_2F_6 (and NF_3 and SF_6), most are unable to abate CF_4 (potentially because of its higher chemical stability). Other problems with this method include the large amounts of water required and the wastewater that is created and requires treatment for fluorides (Chang and Chang, 2006). On the other hand, they produce little or no NO_x. EPA estimated the cost of a combustion/catalytic decomposition system, assuming a 99 percent emission reduction efficiency, at $250,000 per every four etching chambers in capital costs plus $19,750 per every four etching chambers in annual operational costs. No cost savings result from this technology (EPA, 2006a).

Substitutes: Unfortunately, because of the unique, strongly inert nature of PFCs, no excellent substitutes have been found. Tests were conducted with ClF_3, but it is too reactive and has undesirable byproducts of HCl and HF. Two very promising possibilities are substituting NF_3 or C_3F_8 for C_2F_6. Despite the fact that these are also GHGs with high GWPs, they both have higher utilization efficiencies than C_2F_6, resulting in significant reduction in total CO_2-equivalent emissions (Chang and Chang, 2006).

NF_3 remote cleaning technology: EPA estimates the cost of NF_3 remote cleaning technology, assuming a 95 percent emission reduction efficiency, as $59,000 in capital costs per chamber plus $11,000 per chamber in annual operations and $3,800 per chamber in input cost (reflecting the price difference between NF_3 and C_2F_6), leading to a total cost of $14,800 per chamber. Cost savings can be found in reduced chamber cleaning times (up to 30-50 percent faster than C_2F_6 cleaning) and decreases in the number of cleanings between wafer passes. These savings are significant, allowing for a capital recovery in an estimated 9 months or less. This means facilities receive a cost savings of one and one-third times the capital cost, or $79,867 per chamber on an annual basis (EPA, 2006a).

C_3F_8 Replacement: Because this is a straight substitution, there are no capital or annual costs and no annual cost savings. There is an assumed 85 percent emission reduction efficiency for C_3F_8 substitution (EPA, 2006a).

NF_3: Alternatives

Alternatives to NF_3 in the electronics industry do exist. The chemical company Linde installs systems that generate fluorine on-site at LCD panel and semiconductor facilities. The system splits hydrogen fluoride into fluorine (F_2)—which has a GWP of zero—and takes less energy than the NF_3 process. However, the upfront costs are higher because F_2 must be generated on site, since it can't be shipped in bottles like NF_3 due to its toxicity. Toshiba Matsushita Display, Samsung, and LG have installed systems that generate F_2 on site at some of their LCD and semiconductor facilities, replacing the use of NF_3 and SF_6. However, due to the toxicity of F_2, the photovoltaic industry is reluctant to use it. Nevertheless, Paul Stockman of Linde remarks that "fluorine will become essential in thin-film solar manufacturing, because faster cleaning times mean a substantial boost in productivity" (Linde, 2009). Other semiconductor cleaning agent alternatives to NF_3 include HFE-227me, which belongs to a class of chemicals known as hydrofluoroethers (HFEs).

Roof and Pavement Reflective and Emissive Properties

Because of the energy requirements for cement production, conventional cement concrete produces more carbon dioxide equivalent emissions on a life-cycle basis than does asphalt concrete, even though cement concrete has a higher albedo. However, there is evidence that switching from conventional to high-albedo asphalt concrete has a net climate benefit, as does switching from conventional to high-albedo cement concrete.

There are several technologically feasible methods of increasing the albedo of asphalt concrete or cement concrete pavements. For cement concrete, 50-70 percent of the gray Portland cement can be replaced with slag, a by-product of iron production that has a higher albedo and requires less energy to produce than gray Portland cement (Boriboonsomsin and Reza, 2007). There is no additional cost to using slag cement where slag is locally available (Tsakiridis et al., 2008). The Slag Cement Association (2002) reports that slag cement is less permeable than conventional cement, which could be a disadvantage in applications where storm water management is a priority.

For asphalt concrete, a higher-albedo aggregate can be used at no additional cost (Ting et al., 2001). However, the impact on pavement albedo is small, because asphalt's low albedo comes from the dark bitumen binder. This problem can be minimized using chip seals, a technique involving laying high-albedo aggregate on top of an asphalt surface. However, this technique costs more than conventional asphalt concrete. Furthermore, as it changes the texture of the road surface, it may not produce a net climate benefit on roads with heavy traffic (EPA, 2008b; Santero and Horvath, 2009).

Table A.1 lists installed costs for some paving materials as documented by the EPA (2008b). These are not life-cycle costs, as they do not include benefits from reduced maintenance or from storm water management.

Material/Process	**Cost per square foot**
1. Asphalt with light-colored aggregate	$0.10-0.50
2. Conventional concrete with gray Portland cement	$0.30-0.50
3. Chip seals with light aggregate	$0.10-0.15
4. Ultra-thin whitetopping	$1.50-6.50
5. Microsurfacing	$0.35-0.65

(Note: 1-2 represent the entire paving material, while 3-5 are surface applications; the cost of the base material is not included.)

Ting et al. (2001) find that replacing conventional asphalt with high-albedo asphalt on urban roadways saves $1.10-$11.20 per square yard (with estimates concentrated between $1.10-$2.50) when reduced maintenance costs are taken into account. The savings depends on the type of material used, the condition of the road, and the level of traffic.

Table A.2 lists available paving materials and their albedo. Data is compiled from EPA (2008b) for rows 1-2, 5-8 and from Boriboonsomsin and Reza (2007) for rows 3-4.

Material/Process	**Albedo (new unless otherwise noted)**
Conventional asphalt	0.05, increasing with age to 0.15-0.20
Conventional concrete	0.35-0.40, decreasing with age to 0.25-0.30
1. Asphalt with light-colored aggregate	0.15-0.20
2. Concrete with white instead of gray cement	0.70
3. Concrete with 60% fly ash replacing cement	0.245
4. Concrete with 70% slag replacing cement	0.582
5. Resin-based pavement	Varies
6. Chip seals: light-colored aggregate laid on top of asphalt	0.20, decreasing with age
7. Whitetopping or ultra-thin whitetopping: a layer of concrete over an asphalt base	0.35-0.40
8. Microsurfacing: a thin layer of material used for sealing; high-albedo options exist	0.35

Appendix III: Cradle-to-grave emission factors for synthetic gases

Gas	Usage	Approx. % of Use	Emission Factor (%)			
			Production	Use	Servicing	Disposal
HFCs/ ODSs	Refrigerants	50	30[1]	20[1]	55[1]	100[1]
SF_6	Electric power system applications	80	0.1-1[2]	5-10[3]	10-20[3]	
	Semiconductor and thin film production	10	0.1-1[2]			
	Magnesium production	10	0.1-1[2]	100		
PFCs	Aluminum production	40	100[4]			
	Electronic and semiconductor manufacturing	60	0.1-1[2]			
NF_3	Solar photovoltaic manufacture	3	1-3[5]	0.05-0.18[5]		0[5]

[1] Centre D'energetique, 2004
[2] IPCC, 2000
[3] Bessede et al., 2006
[4] EPA, 2002
[5] Fthenakis et al., 2008

The above table shows emission factors for selected uses of non-CO_2 GHGs. We attempt to elucidate how efficient each step is in a GHG's use. Refrigerants, which make up about 50 percent of HFC and ODS emissions, have particularly high emissions factors. For instance, for every two units of refrigerant produced for sale, almost one unit is emitted at the production plant. Also, a fifth of refrigerants in coolers will leak out during the use of the machine. Furthermore, all of the refrigerants in a cooler will leak out once it is disposed unless active recovery or destruction of the gases is undertaken. This table also highlights some unintended consequences of gas use. NF_3 is used as a replacement to PFCs in cleaning vapor deposition units because it can be destroyed almost completely (approximately 99.9 percent) at the site of use. However, between 1 and 3 percent of NF_3 currently produced is emitted during the production of the gas, changing the party responsible for emissions, but not necessarily cutting down on the total emissions. Of further note, data for losses during transportation of the gases to the sites is not listed, as it is not readily available.

Appendix IV: Calculation of CO_2 Offset from Cool Roofs and Pavements

Below are the calculations for the CO_2 equivalencies for cool roofs and pavements that we use in our policy recommendations.

Key assumptions:

- Radiative forcing change for 0.01 albedo change: 1.27 W/m^2 (Akbari et al., 2008)
- Surface area of Earth: 510,072,000,000,000 m^2
- CO_2 radiative forcing over time (see chart, adapted from TEAP, 2009)
- Projected area of average house, i.e. house footprint: 100 m^2
- Urban road area: 530,000,000,000 m^2 roofs (Akbari et al., 2008)
- Urban roof area: 380,000,000,000 m^2 roofs (Akbari et al., 2008)

Calculations:

Normalize radiative forcing with respect to surface area of Earth:

$$2.5 * 10^{-15}\ W/m^2_{roof}/m^2_{earth}$$

$$(= 1.27\ W/m^2_{roof}/510{,}072{,}000{,}000{,}000\ m^2_{earth})$$

To compare with CO_2, the integral radiative forcings of time are calculated. The red shaded region represents the integrated forcing for a surface that lasts 20 years (like a roof). This is compared to forcing of CO_2 over 100 years (blue shaded region) as is standard with 100-year GWP calculations.

From this we find that 1 m^2 of 0.01 albedo change over 20 years corresponds to 0.6 kg CO_2 emitted. If we were only integrating up to 20 years, in GWP_{20} calculations, the value would be 2.1 kg CO_2. If the albedo was changed for the full 100 years, it would be equivalent to 2.9 kg CO_2 emitted.

Thus, a 100 m^2 roof with an albedo change of 0.25 which lasts 20 years has an equivalent forcing over 100 years of 1.5 tCO_2.

$$\left(= \frac{0.6\ kg\ CO_2}{m^2 * 0.01\ albedo} * \frac{1\ tCO_2}{1000\ kg\ CO_2} * 0.25\ albedo * 100m^2\right)$$

Similarly, 100 m^2 of road with an albedo change of 0.1 which lasts 20 years has an equivalent forcing over 100 years of 0.6 tCO_2.

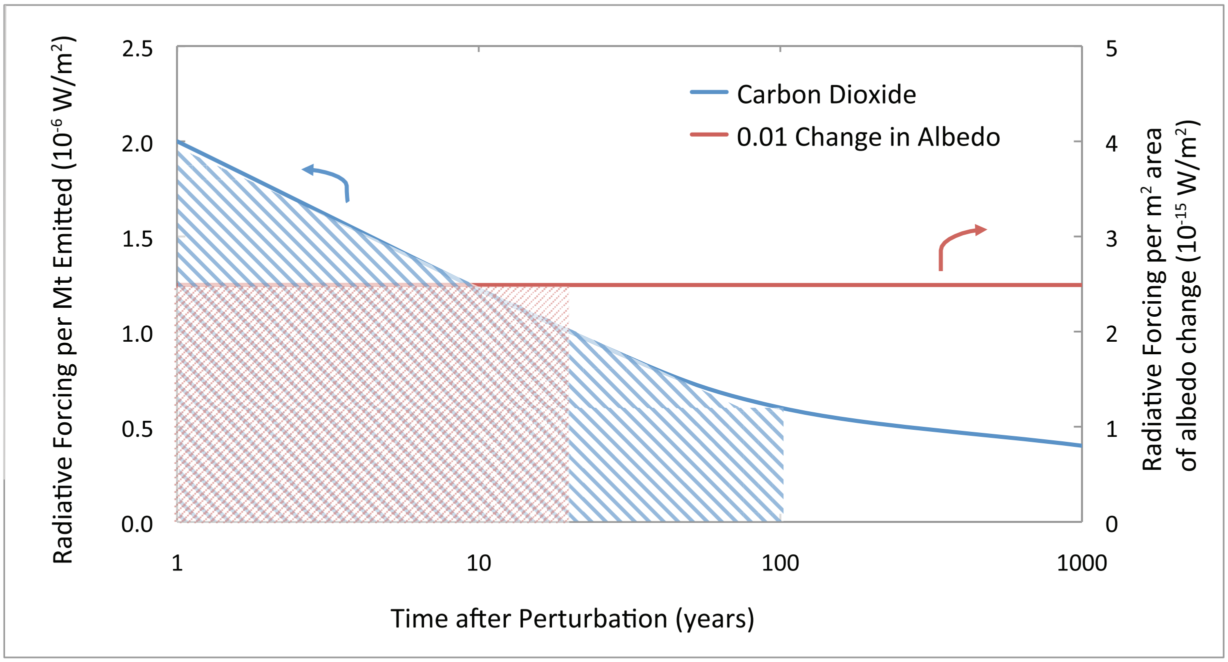
Increasing all road albedo by 0.1 and all roof albedo by 0.25 for 20 years would have an equivalent forcing over 100 years as 8.9 $GtCO_2$.

$$\left(= \frac{0.6\ kg\ CO_2}{m^2 * 0.01\ albedo} * \frac{1\ tCO_2}{1000\ kg\ CO_2} * 0.1\ albedo * 530{,}000{,}000{,}000m^2 + \frac{0.6\ kg\ CO_2}{m^2 * 0.01\ albedo} * \frac{1\ tCO_2}{1000\ kg\ CO_2} * 0.25\ albedo * 380{,}000{,}000{,}000m^2)\right)$$

The calculations performed for the best policy opportunities are as follows:

10 large parking lots or 200 lane-miles of local roads (980,000 m^2 of pavement) = 5.9 $ktCO_2$

50,000 homes (5,000,000 m^2 of roofs) = 75 $ktCO_2$



Glossary

ACEEE: American Council for an Energy-Efficient Economy

Albedo: Fraction of solar radiation reflected from a surface

ASHRAE: American Society of Heating, Refrigerating, and Air-conditioning Engineers

CAA: Clean Air Act

CAFE: Corporate average fuel economy

CARB: California Air Resources Board

CEM: Clean Energy Ministerial

CFCs: Chlorofluorocarbons

CH_4: Methane

CO_2: Carbon Dioxide

DOE: United States Department of Energy

DOT: Department of Transportation

EC: European Commission

EIA: Environmental Investigation Agency

EPA: United States Environmental Protection Agency

Equivalent Carbon Dioxide (CO_2eq): The amount of CO_2 that would cause the same radiative forcing as a certain mass of the agent. The CO_2e is calculated from the GWP of the agent, and is the mass of the agent multiplied by the GWP.

EU: European Union

F-gas: A fluorinated greenhouse gases, such as HFCs, PFCs and SF_6.

HCFCs: Hydrochloroflurocarbons

HFCs: Hydrofluorocarbons

HUD: U.S. Department of Housing and Urban Development

IAI: International Aluminum Institute

IFA: International Fertilizer Industry Association

F-gas: A gas that contains one or more fluorine atoms

FAO: Food and Agriculture Organization

GEF: Global Environment Facility

GHG: Greenhouse gas

GWP (Global Warming Potential): The potential a gas has in contributing to global warming relative to CO_2 over a specified period of time. The measurement is calculated as a time-integral of the radiative forcing of an emitted pulse of the gas, relative to the time-integral of the radiative forcing of CO_2 for the same mass.

$$GWP(H)_i = \frac{\int_0^H a_i c_i(t)dt}{\int_0^H a_{CO_2} c_{CO_2}(t)dt}$$

Where:

a = radiative forcing of gas
c = concentration of gas
H =time horizon for integration
i = name of gas

GMI: Global Methane Initiative

IIASA: International Institute for Advanced Systems Analysis, Vienna, Austria

IGSD: Institute for Governance and Sustainable Development

IPCC: Intergovernmental Panel on Climate Change

LCCP: Life cycle climate performance

LEED: Leadership in Energy and Environmental Design

MEF: Major Economies Forum

MVAC: Motor vehicle air conditioning

N_2O: Nitrous oxide

NF_3: Nitrogen trifluoride

NGOs: Non-governmental organizations

NHTSA: National Highway Traffic Safety Administration

NRDC: Natural Resources Defense Council

ORNL: Oak Ridge National Laboratory

Ozone Depleting Potential (ODP): The potential a gas has in destroying the ozone layer. Measured as the amount of loss to the ozone layer by a species relative to the amount of loss by CFC-11.

ODS: Ozone-depleting substance

OECD: Organization for Economic Co-operation and Development

PFCs: Perfluorocarbons

PFPB: Point feed prebake systems

PM: Particulate matter

PV: Photovoltaic

Radiative Forcing (RF): The instantaneous measure of energy in W/m2 added to the climate system from absorbed radiation by an agent. Positive forcing indicates energy trapped within the climate system, and a warming tendency. Negative forcing indicates more energy reflected and a cooling tendency.

RRA: Refrigerant Reclaim Australia

SF_6: Sulfur hexafluoride

SNAP: Significant New Alternatives Policy

TEAP: Technology and Economic Assessment Panel of the Montreal Protocol on Substances that Deplete the Stratospheric Ozone Layer

Thermal emissivity: the rate of radiant heat emitted by a given surface relative to the radiant heat emitted by a black body (also referred to as thermal emittance)

ULSD: Ultra-low-sulfur diesel

UN: United Nations

UNEP: United Nations Environment Program

UNFCCC: United Nations Framework Convention on Climate Change

USDA: United States Department of Agriculture

WSC: World Semiconductor Council

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