Clearinghouse of Technological Options for Reducing Anthropogenic Non-CO_2 GHG Emissions from All Sectors

(Contract No.: CARB 05-328)

Prepared for:

State of California Air Resources Board
Research Division
PO Box 2815
Sacramento, CA 95812

Prepared by:

Jeff Kuo, Ph.D., P.E. (Principal Investigator)

Dept. of Civil and Environmental Engineering
California State University, Fullerton
800 N. State College Blvd.
Fullerton, CA 92834-6870
(714) 278-3995; jkuo@fullerton.edu

May 14, 2008

DISCLAIMER

ACKNOWLEDGMENTS

The main objective of this project is to summarize available information on technological options for reducing anthropogenic non-CO_2 greenhouse gas emissions. The project team would like to express its appreciation to professionals all over the world who have spent efforts in developing technologies and measures toward emission reductions of non-CO_2 greenhouse gases. Their work provides humankind with valuable tools for dealing with important global warming issues and their work is the basis of this project. Although this project team has tried its best to conduct a comprehensive literature search and to include as many findings as possible, the project team realizes that some may still be missing from this report and would like to apologize for any omissions.

The project team would also like to express its gratitude toward Contractor Manager, Mr. Steve Church of CARB, who provided great guidance to the team. The project team acknowledges the reviewers of the task reports and the draft final report for their valuable comments and suggestions.

Jeff Kuo, Professor of Department of Civil and Environmental Engineering at California State University, Fullerton (CSUF), served as the principal investigator of this project. Ms. Barbarly McConnell, reference and instruction/science librarian at CSUF, was the co-PI. Ms. McConnell guided the project team in the literature search and served as the technical writer for the final report. Many CSUF graduate students also made contributions to this project including Momoe Kanada, Emiko Ishihara, Ravi Singh, Lindia Liu, Vladimir Carino, Lisa Zarubick, Dimple Patel, and Can Canbazoglu.

The Report was submitted in fulfillment of CARB contract number 05-328, *Clearinghouse of Technological Options for Reducing Anthropogenic Non-CO_2 GHG Emissions from All Sectors*, by California State University, Fullerton, under the sponsorship of the California Air Resources Board. Work was completed as of March 10, 2008.

TABLE OF CONTENTS

Chapter 4 – High GWP Gases

Chapter 5 – Black Carbon

Appendices

LIST OF TABLES

Page

LIST OF FIGURES

ABSTRACT

This project, *Clearinghouse of Technological Options for Reducing Anthropogenic Non-CO_2 GHG Emissions from All Sectors*, gathered and evaluated information and data available in the literature regarding technological options for reducing anthropogenic non-CO_2 greenhouse gas (NCGG) emissions from all sectors in California. Emissions sources of the NCGGs (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) and black carbon in California were first identified. Data and information regarding reduction efficiency, market penetration, technical availability, service lifetime, and costs on many viable technological options were then gathered, evaluated, and presented in a systematic way for easy comparison and use. The findings of this project can serve as the basis for a web site to disseminate and act as a clearinghouse for non-CO_2 greenhouse gas control technology information. Employment of an appropriate control technology for a given source would achieve a net reduction in NCGG emissions and in its contribution to climate change.

EXECUTIVE SUMMARY

Background

California is vulnerable to the impacts of climate change. Greenhouse (GHG) emissions contribute to the climate change. On June 1, 2005 the California Governor signed Executive Order S-3-05 that established the GHG targets. The targets call for a reduction of GHG emissions to 2000 levels by 2010; a reduction to 1990 levels by 2020; and a reduction to 80% below 1990 levels by 2050. The main GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The non-CO_2 greenhouse gases (NCGGs) emissions in California were 75 $MMT_{CO2\text{-}Eq.}$ in 2004, approximately 18% of the total GHG emissions; out of this 18%, 7.6% came from nitrous oxide, 6.4% from methane, and 3.2% from HFCs, PFCs, and SF_6.

NCGGs have recently gained attention because of their higher global warming potentials (GWPs) and abundance of cost-effective and readily-implementable technological options available for achieving significant emission reductions. The overall objective of this project was to develop a clearinghouse of technological options for reducing anthropogenic, NCGG emissions from sectors that are relevant to California. Black carbon, an emerging substance of concern for global warming, was also included. The findings of this project will contribute to better characterization of cost-effective opportunities for emission reductions of NCGGs from all sectors. The findings can also serve as a basis for a web site to disseminate and act as a clearinghouse for information on NCGG emission control technologies.

Methods

The project started with a literature search to identify sources of NCGG emissions from various sectors in California. Electronic databases that are available at the library of California State University at Fullerton (CSUF) were used in the literature search. These databases included: *Applied Science and Technology Abstracts*, *Compendex* (accessed via Engineering Village), *Environmental Abstracts* (accessed via LexisNexis Environmental), *Web of Science*, *ScienceDirect*, *PapersFirst*, and *ProceedingsFirst*. After the emission sources were identified, another comprehensive literature search was conducted to identify available technological options for NCGG emission reductions. A study was then conducted on gathered information to evaluate identified technological options for their applicability in California. Some of the technological options identified from the literature search are already in use, but many of them are still in conceptual, bench-scale studies, or R&D stages. To serve as a clearinghouse, this report includes information of as many technological options as possible. For those options with sufficient and definite information, reduction efficiency, market penetration, technical applicability, service lifetime, and costs are summarized in tables for easier comparison and use. With these cost data and the expected lifespan of a given technological option, one can easily derive a cost estimate for implementing an option. More detailed data and information on these technological options and some additional options are provided in the appendices. It should be noted that data that are specific to California have the first priority, over those with nation-wide or global perspectives, for incorporation in this final report.

Results

The top contributors for CH_4 emissions in California, in the order of magnitude, are landfills (30.2%), enteric fermentation (25.9%), manure management (21.6%), wastewater treatment (6.1%), natural gas systems (5.0%), stationary combustion, (4.7%), mobile combustion (2.2%), rice cultivation (2.2%), petroleum system (1.8%), and field burning of agricultural residues (0.4%). Many viable technological options for emission reductions for these sectors, especially in oil and natural gas systems, landfills, manure management, enteric fermentation, and wastewater treatment are identified and described in Chapter 2 of the report.

The contributors for N_2O emissions in California, in the order of magnitude, are agricultural soil management (57.5%), mobile combustion (35.3%), human sewage (3.2%), manure management (2.7%), stationary combustion (0.6%), nitric acid production (0.5%), field burning of agricultural residues (0.2%), and municipal solid waste combustion (0.1%). Many viable technological options for emission reductions for these sectors, especially in agricultural soil management, manure management, mobile and stationary combustion, nitric acid production, and wastewater treatment are identified and described in Chapter 3 of the report.

HFCs and PFCs are commonly used as alternatives to several classes of ozone-depleting substances (ODS). These compounds, along with sulfur hexafluoride (SF_6), are potent greenhouse gases with high global warming potentials (GWP). Substitution of ODS with HFCs and PFCs is the dominant emission source of high-GWP gases in California and it represents 88.8% of total high-GWP gases emissions. Electrical transmission and distribution (7.2%) and semiconductor manufacture (4.0%) are the other two significant emission sources of high-GWP gases in California. Many viable technological options for emission reductions for all these three sectors are identified and described in Chapter 4 of the report.

No statewide black carbon emission inventories were found from the literature search. However, potential sources of black carbon emissions were described and technological options for emission reductions were presented in Chapter 5 of the report. Chapter 6 presents a brief summary and conclusions of this project.

Conclusions

This project, *Clearinghouse of Technological Options for Reducing Anthropogenic Non-*CO_2 *GHG Emissions from All Sectors*, gathered and evaluated information and data that are available in literature regarding technological options for reducing anthropogenic NCGG emissions from all sectors in California. Emissions sources of the NCGGs (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) and black carbon in California were first identified. Data and information regarding reduction efficiency, market penetration, technical availability, service lifetime, and costs on many viable technological options were then gathered, evaluated, and presented in a systematic way for easy comparison and use. The findings of this project can serve as the basis for a web site to disseminate and act as a clearinghouse for non-CO_2 greenhouse gas control technology information. Employment of an appropriate control technology for a given source would achieve a net reduction in NCGG emissions and in its contribution to climate change.

CHAPTER 1
INTRODUCTION

1.0 – Introduction

California is vulnerable to the impacts of climate change. Greenhouse (GHG) emissions contribute to the climate change. On June 1, 2005 the California Governor signed Executive Order S-3-05 that established the GHG targets. The targets call for a reduction of GHG emissions to 2000 levels by 2010; a reduction to 1990 levels by 2020; and a reduction to 80% below 1990 levels by 2050. The main GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

In the past, the climate mitigation studies were focused on CO_2, especially from energy-related sources. In the past few years, however, non-CO_2 greenhouse gases (NCGGs) have rapidly gained attention because of their higher global warming potentials (GWPs) and abundance of cost-effective and readily-implementable technological options available for achieving significant emission reductions. Studies have found that abatement options for several of the NCGG sources are relatively inexpensive. In addition, NCGG emission reductions may provide a more rapid response in avoiding climate impacts by focusing on short-lived gases (Lucas *et al.*, 2006; de la Chesnaye *et al.*, 2001).

The overall objective of this project was to develop a clearinghouse of technological options for reducing anthropogenic, NCGG emissions from sectors that are relevant to California. Black carbon, an emerging substance of concern for global warming, was also included. To achieve this goal, specific project tasks were completed, including (1) identification of sources of NCGG emissions from various sectors in California, (2) identification of available technological options for NCGG emission reductions through a comprehensive literature search, (3) evaluation of the identified technological options for their applicability in California, and (4) report preparation. The findings of this project will contribute to better characterization of cost-effective opportunities for emission reductions of NCGGs from all sectors. The findings can also serve as a basis for a web site to disseminate and act as a clearinghouse for information on NCGG emission control technologies. Employment of an appropriate control technology for a given source would achieve a net reduction in NCGG emissions and in its contribution to climate change.

1.1 – Methods and Approaches

1.1.1 – Literature Search

A comprehensive literature search was conducted on sources of NCGG emissions and abatement technologies for emission reductions. Electronic databases that are available at the library of California State University at Fullerton (CSUF) were used in the literature search. These databases included: *Applied Science and Technology Abstracts*, *Compendex* (accessed via Engineering Village), *Environmental Abstracts* (accessed via LexisNexis Environmental), *Web of Science*, *ScienceDirect*, *PapersFirst*, and *ProceedingsFirst*. The search typically started in *Compendex* and was repeated in *Environmental Abstracts*, then *Web of Science*, and finally *ScienceDirect*. *RefWorks*, a web-based bibliographic management service used for storing and organizing citations as well as automatically formatting bibliographies, was used to manage the records found in the literature search. More than 800 relevant references have been identified.

In addition to the library databases, Internet search engines, such as Google.com and Yahoo.com, were used to find websites that are relevant to non-CO_2 GHG gases. A handful of web sites were identified that contain useful information, especially reports that are typically not found from the search of library databases. A few key national and international conferences were also identified.

1.1.2 – Sectors for Emission Sources

Although the emission sources can be categorized into economic sectors (i.e., residential, commercial, industrial, agricultural, transportation, electricity generation, and U.S. territories), six potential source sectors, as defined by United Nations Intergovernmental Panel on Climate Change (IPCC), were used in this report:

1. Energy
2. Industrial processes
3. Solvent use
4. Agriculture
5. Land-use change and forestry
6. Waste

This categorization was chosen to be consistent with the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1997) and United Nations Framework Convention on Climate Change's *2003 UNFCCC Guidelines on Reporting and Review* (UNFCCC, 2003). The same sectors were used in the most recent inventory report by U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004* (USEPA, 2006).

The rest of this section presents a brief discussion on sources of GHG emissions from each of these six sectors. It should be noted that some of these sectors and/or their sub-sectors were developed with carbon dioxide in mind; the NCGG emissions from these sectors are negligible (e.g., industrial processes such as lime manufacture). In addition, although the nationwide NCGG emissions from some sub-sectors are significant, they may not be relevant to California since the activities associated with these emissions do not exist in California (e.g., adipic acid production). In the subsequent chapters, those irrelevant sectors and sub-sectors are removed from further consideration and discussion.

1.1.2.A – Energy

Energy-related activities are the primary sources of anthropogenic GHG emissions in the United States. They accounted for 86 percent of total emissions on a carbon equivalent basis in 2004. Thirty-nine percent of nation-wide methane emissions are energy-related, while 15% of nitrous oxide emissions are energy-related. There are ten sub-sectors considered in the EPA's inventory report (USEPA, 2006):

1. Stationary combustion
2. Mobile combustion
3. Coal mining
4. Abandoned underground coal mines
5. Petroleum systems

6. Natural gas systems
7. Municipal solid waste combustion
8. Natural gas flaring and ambient air pollutant emissions from oil and gas activities
9. International bunker fuels
10. Wood biomass and ethanol consumption

1.1.2.B – Industrial Processes

GHG emissions are also produced as a by-product of various non-energy related industrial activities. For example, raw materials can be chemically transformed and this transformation may result in emissions of GHGs including carbon dioxide, methane, and nitrous oxide. The processes addressed in the EPA's inventory report include the following twenty industries (USEPA, 2006):

1. Iron and steel production
2. Cement manufacture
3. Ammonia manufacture and urea application
4. Lime manufacture
5. Limestone and dolomite use
6. Soda ash manufacture and consumption
7. Titanium oxide production
8. Phosphoric acid production
9. Ferroalloy production
10. Carbon dioxide consumption
11. Petrochemical production
12. Silicon carbide production
13. Nitric acid production
14. Adipic acid production
15. Substitution of ozone depleting substances
16. HCFC production
17. Electrical transmission and distribution
18. Aluminum production
19. Semiconductor manufacture
20. Magnesium production and processing

1.1.2.C – Solvent and Other Product Use

GHG emissions can be produced as a by-product of various solvents and other product uses. However, in the United States, emission from nitrous oxide product usage is the only source of GHG emissions from this sector, and it accounted for less than 0.1 percent of total U.S. anthropogenic GHG emissions on a carbon equivalent basis in 2004 (USEPA, 2006).

1.1.2.D – Agricultural

A variety of agricultural activities contribute to GHG emissions, with methane and nitrous oxide being the primary ones. The main emission sources in this sector can be grouped into five sub-sectors (USEPA, 2006):

1. Enteric fermentation (CH_4)
2. Manure management (CH_4 and N_2O)
3. Rice cultivation (CH_4)
4. Agricultural soil management (N_2O)
5. Field burning of agricultural residuals (CH_4 and N_2O)

1.1.2.E – Land-use Change and Forestry

IPCC's *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC, 2003) recommends reporting fluxes according to changes within and conversions between certain land-use types (forestland, cropland, grassland, settlements, and wetlands). For its inventory report, U.S. EPA estimated greenhouse gas fluxes from the following sub-sectors (USEPA, 2006):

1. Forest land remaining forest land
2. Land converted to forest land
3. Croplands remaining croplands
4. Lands converted to croplands
5. Settlement remaining settlements
6. Lands converted to settlements

1.1.2.F – Waste

Waste management and treatment activities are sources of GHG emissions, especially for methane and nitrous oxide. Landfills were the largest source of anthropogenic methane emissions in 2004, accounting for 25% of total methane emissions in the United States. Wastewater treatment accounts for another 7% of the U.S. methane emissions. Discharge of wastewater treatment effluents in receiving waters and the treatment process itself are the sources of nitrous oxide emissions. The following waste and waste management groups were addressed in the inventory report by USEPA (USEPA, 2006):

1. Landfills
2. Wastewater treatment
3. Human sewage (domestic wastewater)

1.1.3 – Importance of Emission Sources

As mentioned, the overall objective of this project is to develop a clearinghouse of technological options for reducing anthropogenic, NCGG emissions from sectors that are relevant to California. To better characterize cost-effective and applicable opportunities for NCGG emission reductions, knowledge on relative magnitudes of emissions from each source is important. The GHGs in the atmosphere can contribute to the global warming effect both directly and indirectly. The IPCC developed the Global Warming Potential (GWP) concept to compare the ability of each GHG to trap heat in the atmosphere relative to carbon dioxide (CO_2). Table 1-1 tabulates the GWP values based on a 100-year time horizon from IPCC's second (1996) and third (2001) assessment reports.

Table 1.1 – 100-Year GWP Estimates from Two IPCC Assessment Reports

Gas	1996 IPCC GWP	2001 IPCC GWP
Carbon Dioxide	1	1
Methane	21	23
Nitrous Oxide	310	296
HFC-23	11,700	12,000
HFC-125	2,800	3,400
HFC-134a	1,300	1,300
HFC-143a	3,800	4,300
HFC-152a	140	120
HFC-227ea	2,900	3,500
HFC-236fa	6,300	9,400
Perfluoromethane (CF_4)	6,500	5,700
Perfluoroethane (C_2F_4)	9,200	11,900
Sulfur Hexafluoride	23,900	22,200

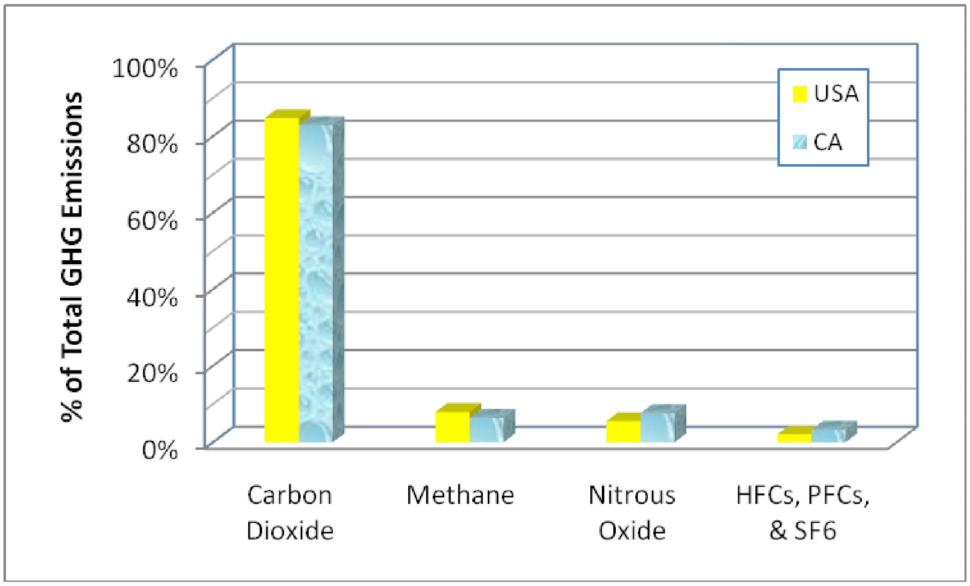
The GWP of a GHG is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of one kilogram (kg) of this GHG to that of 1 kg of CO_2. Based on the 2001 IPCC estimates, the GWPs of methane and nitrous oxide over 100-yr time horizon are 23 and 296, respectively; those for HFCs range from 120 to 12,000, for PFCs range from 5,700 to 11,900, and 22,200 for SF_6 (IPCC, 2001). Since the reference gas used is CO_2, the GWP-weighted emissions are often reported in 10^{12} grams (teragrams) of CO_2 equivalent (Tg CO_2 Eq.) or one million metric ton CO_2 equivalent ($MMT_{CO2\text{-}Eq.}$). One $MMT_{CO2\text{-}Eq.}$ is equal to one Tg CO_2 Eq., which is used in the most recent inventory report by California Energy Commission (CEC), titled *Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004* (CEC, 2006).

Table 1.2 presents a comparison of GHG emissions in the United States and California. It should be noted that these emission estimates were derived by using the 1996 IPCC GWP values; and the CA estimates were extracted from an updated inventory report (CEC, 2007). The NCGG emissions in California were 75 $MMT_{CO2\text{-}Eq.}$ in 2004, approximately 18% of the total GHG emissions; out of this 18%, 7.6% came from nitrous oxide, 6.4% from methane, and 3.2% from HFCs, PFCs, and SF_6. As shown in the table, GHG emissions in California account for approximately 6.2% of the nationwide emissions with CO_2 as the dominant GHG in both California and the USA. Methane is the second dominant GHG and nitrous oxide is the third in the United States, while the rankings for these two compounds are in a reverse order in California (see Figure 1.1). The CA/USA ratios for methane, nitrous oxide, and high GWP gases are 5.0%, 8.6%, and 9.9%, respectively. Plausible causes for the differences in these ratios include (1) differences in the composition of the contributing sectors (e.g., no active coal mines, an important source of methane emissions, in CA), (2) differences in relative intensity of a sub-sector (e.g., agricultural activity, the dominant source for N_2O emission, in CA is higher than nationwide-average), and (3) differences in methods and assumptions used in deriving these emission estimates. In the subsequent chapters, the emissions of an NCGG from a sector and/or a sub-sector in the USA and California will frequently be compared to illustrate the significance of each source.

Table 1.2 – Comparison of GHG Emissions in the USA and California

	USA (2004)		**California (2004)**		
Gas	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Carbon Dioxide	5,988	84.6%	364	82.8%	**6.1%**
Methane	557	7.9%	28	6.4%	**5.0%**
Nitrous Oxide	387	5.5%	33	7.6%	**8.6%**
HFCs, PFCs, and SF_6	143	2.0%	14	3.2%	**9.9%**
Total	**7,074**	100%	**439**	100%	**6.2%**

Figure 1.1 – Comparison of GHG Emissions in the USA and California



1.1.4 – Evaluation of Technological Options

Some of the technological options identified from the literature search are already in use, but many of them are still in conceptual, bench-scale studies, or research and development (R&D) stages. To evaluate the applicability and implementability of a technological option, it is important to have the data on reduction efficiency (RE), market penetration (MP), technical applicability (TA), service lifetime, and costs (capital and O&M). To serve as a clearinghouse, this report includes information on as many technological options as possible. Those options with sufficient and definite information on lifetime, RE, MP, TA, and costs are summarized in tables for easier comparison and use. More detailed data and information on these technological options are provided in the appendices.

The reduction efficiency tells the percentage that emission can be mitigated by a technological option. In a given source category, the technological option may only be applicable to a portion of the baseline emissions. The percentage of the baseline to which a technological option is applicable is called technical applicability (CEC, 2005). Market penetration is the percentage of emissions from a given source that is expected to be addressed by a given technological option (CEC, 2005). The cost data are presented in year 2000 U.S. dollars per metric ton CO_2 equivalent ($\$/MT_{CO2\text{-}Eq.}$). There are three types of cost data presented in this report for a given technological option. The one-time capital cost reflects the initial investment of the technological option. The annual cost reflects the yearly O&M cost needed to implement the option, while benefits refer to monetary savings, if any, resulting from the implementation of the option (CEC, 2005). In addition, lifetime data are also provided which show the expected lifespan of the project. With these cost data and the expected lifespan of a given technological option, one can easily derive an estimate for implementing an option. However, it should be noted that the data for a given option are often very general in nature and may not be applicable to all the cases.

The data on a given technological option can sometimes be found from various sources, such as reports of California Energy Commission (CEC), CARB, EPA, and some international agencies including United Nations (UN) and International Energy Agency (IEA). This report uses the data that are more specific to California first (e.g., from reports of CEC and CARB). If information from these sources was not available, data specific to the United States are then used, followed by the data that were developed for global perspectives or for other countries.

1.2 – Organization of the Report

Table 1.3 tabulates potential source sectors for emissions of each of the NCGGs. The table was generated after review of the available data and information. The subsequent chapters in this report will address each NCGG individually. Chapter 2 is for methane and Chapter 3 is for nitrous oxide. Due to the similarities between the PFCs, HFCs, and SF_6 with regards to their characteristics and sources, they are grouped as the high-GWP gases and covered in Chapter 4. For black carbon, it has not been included in the GHG inventory reports of the United States and California yet. Although the six-sector approach can be used to report black carbon emissions, most of the literature categorized the emissions into mobile source and stationary source (since combustion is the dominant source of black carbon emissions into the atmosphere). Consequently, discussion on emission sources and technological options of emission reductions in Chapter 5 will use a similar approach, i.e., stationary vs. mobile sources. Chapter 6 presents a brief summary and conclusions of this project.

Table 1.3 – Potential Emission Source Sectors for Each NCGG in California

	CH_4	N_2O	PFCs	HFCs	SF_6	Black Carbon
Energy	√	√				√
Industrial processes	√	√	√	√	√	√
Solvent use		√				
Agriculture	√	√				
Land-use change and forestry	√	√				
Waste	√	√				

References

California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, CEC-600-2006-013, December 22, 2006.

California Energy Commission (2007) “Revisions to the 1990 to 2004 Greenhouse Gas Emissions Inventory Report”, Letter from Rosella Shapiro of CEC to ARB, posted February 2, 2007.

de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

Intergovernmental Panel on Climate Change - IPCC (1996), “Climate Change 1995: The Science of Climate Change”, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change - IPCC (1997), “Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories”, United Nations Intergovernmental Panel on Clime Change.

Intergovernmental Panel on Climate Change - IPCC (2001), “Climate Change 2001: The Science of Climate Change”, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change - IPCC (2003) “Good Practice Guidance for Land Use, Land-use Change, and Forestry”, approved in November, 2003.

Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.

United Nations Framework Convention on Climate Change - UNFCCC (2003) “Guidelines on Reporting and Review”, UNFCCC.

U.S. Environmental Protection Agency (2006) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.

CHAPTER 2

METHANE

2.0 - Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), methane (CH_4) is approximately twenty-three times as effective as carbon dioxide (CO_2) in trapping heat in the atmosphere over a 100-year time horizon (IPCC, 2001). The chemical lifetime of CH_4 in the atmosphere is about twelve years. Since 1750, the global-average atmospheric concentrations of CH_4 have changed from about 700 to 1,745 parts per million by volume (ppmV), a 150% increase (IPCC, 2001). This increase is mainly due to anthropogenic emissions, including emissions from landfills, natural gas and petroleum systems, manure management, coal mining, wastewater treatment, stationary and mobile combustions, and some industrial processes (USEPA, 1999; USEPA 2006a).

Table 2.1 – Summary of Methane Emissions in the USA and California

	USA (2004)		**California (2004)**		
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Landfills	140.9	25.3%	8.4	30.2%	6.0%
Natural Gas Systems	118.8	21.3%	1.4	5.0%	1.2%
Enteric Fermentation	112.6	20.2%	7.2	25.9%	6.4%
Coal Mining	56.3	10.1%	-	-	-
Manure Management	39.4	7.1%	6.0	21.6%	15.2%
Wastewater Treatment	36.9	6.6%	1.7	6.1%	4.6%
Petroleum Systems	25.7	4.6%	0.5	1.8%	1.9%
Rice Cultivation	7.6	1.4%	0.6	2.2%	7.9%
Stationary Combustion	6.4	1.1%	1.3	4.7%	20.3%
Abandoned Underground Coal Mines	5.6	1.0%	-	-	-
Mobile Combustion	2.9	0.5%	0.6	2.2%	20.7%
Petroleum Production	1.6	0.3%	-	-	-
Iron and Steel Production	1.0	0.2%	-	-	-
Field Burning of Agricultural Residues	0.9	0.2%	0.1	0.4%	11.1%
International Bunker Fuels	0.1	0.02%	-	-	-
Total	**556.7**	100%	**27.8**	100%	**5.0%**

Table 2.1 summarizes CH_4 emissions from various sub-sectors in California and in the United States. The data were extracted from the recent inventory reports of USEPA and CEC (USEPA, 2006a; CEC 2006). As shown, CH_4 emissions in California account for approximately 5.0% of the nationwide methane emissions. The top five contributors for CH_4 emissions in the United States are landfills (25.3%), natural gas systems (21.3%), enteric fermentation (20.2%), coal mining (10.1%), manure

management (7.1%), and wastewater treatment (6.6%). The top contributors for CH_4 emissions in California, in the order of magnitude are landfills (30.2%), enteric fermentation (25.9%), manure management (21.6%), wastewater treatment (6.1%), natural gas systems (5.0%), stationary combustion, (4.7%), mobile combustion (2.2%), rice cultivation (2.2%), petroleum system (1.8%), and field burning of agricultural residues (0.4%). The percentage emissions of major sources in the USA and California are also plotted, in a descending order, in Figures 2.1 and 2.2, respectively.

Figure 2.1 – Major Sources of Methane Emissions in the USA

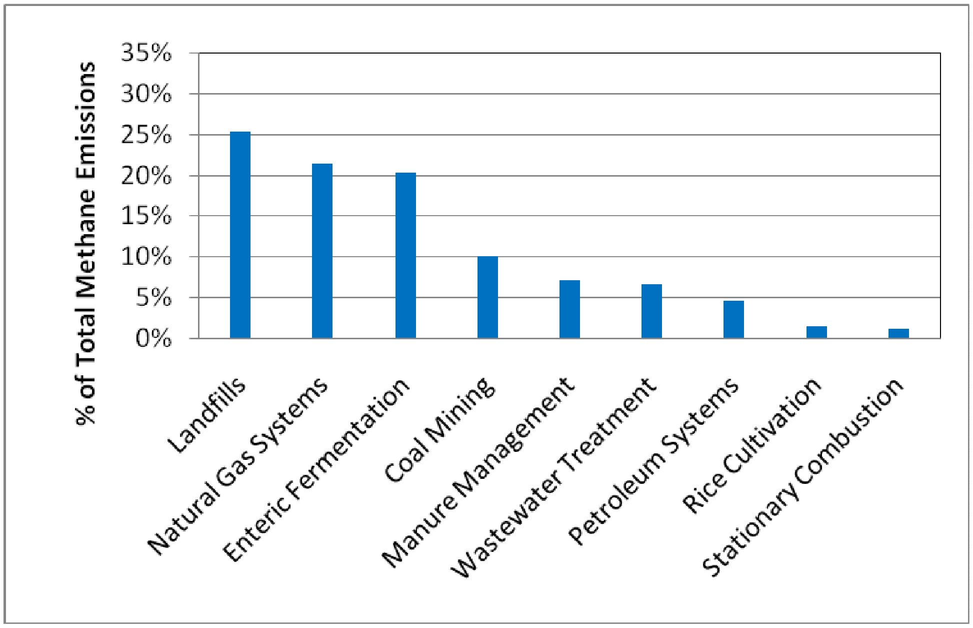
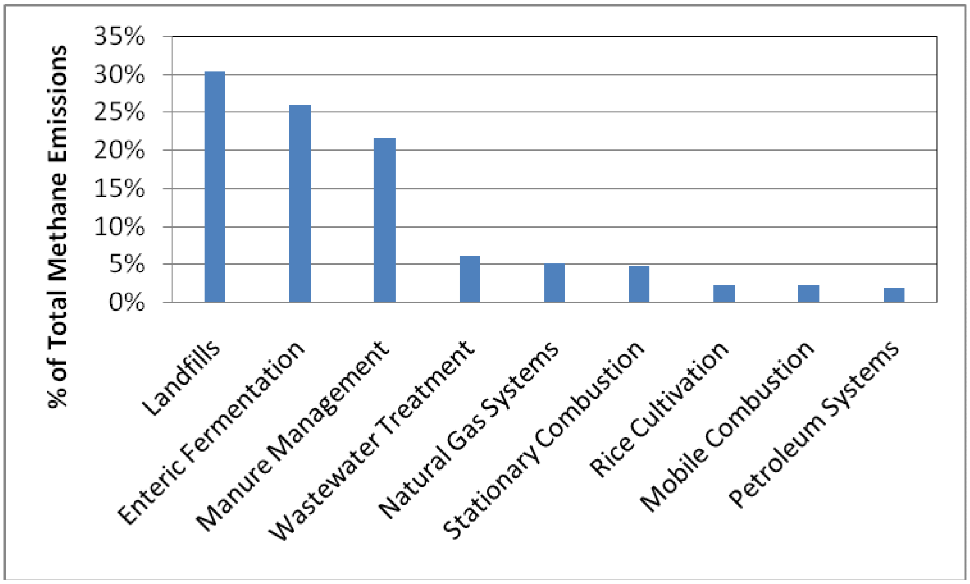


Figure 2.2 – Major Sources of Methane Emissions in California



Since there are no known sources of CH_4 emissions from the sector of solvent use, the following sections describe the sources from the other five major sectors: energy, industrial processes, agriculture, land-use change and forestry, and waste.

2.1 - Energy

Table 2.2 summarizes CH_4 emissions from the energy sector in California and in the United States. As shown, CH_4 emissions in California account for only 1.8% of the nationwide methane emissions from the energy sector. The major contributors for methane emissions in the energy sector in California are natural gas systems (36.8%), stationary combustion (34.2%), mobile combustion (15.8 %), and petroleum systems (13.2%). Figure 2.3 plots the major sources of methane emissions from the energy sector in California in a descending order.

Table 2.2 – Summary of Methane Emissions from Energy Sector in the USA and California

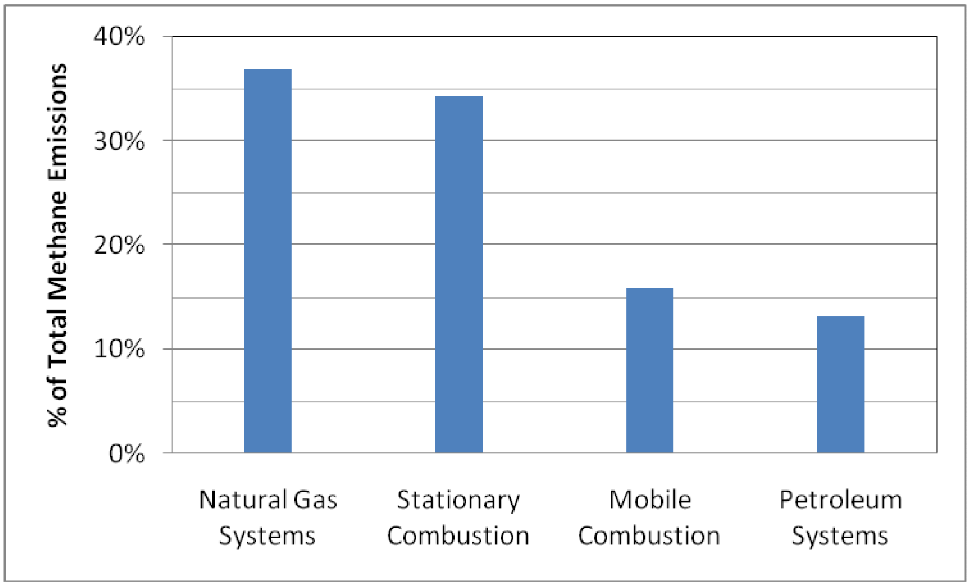
	USA (2004)		**California (2004)**		
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Natural Gas Systems	118.8	55.1%	1.4	36.8%	1.2%
Coal Mining	56.3	26.1%			
Petroleum Systems	25.7	11.9%	0.5	13.2%	1.9%
Stationary Combustion	6.4	3.0%	1.3	34.2%	20.3%
Abandoned Underground Coal Mines	5.6	2.6%			
Mobile Combustion	2.9	1.3%	0.6	15.8%	20.7%
International Bunker Fuels	0.1	0.0%			
Total	**215.8**	100%	**3.8**	100%	**1.8%**

The methane emissions from this energy sector in California were 3.8 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 13.7% of the state's total CH_4 emissions, 27.8 $MMT_{CO2\text{-}Eq.}$ (CEC, 2006).

The following sections discuss five sub-sectors within the energy sector in California, which would have CH_4 emissions; these are:

- Petroleum systems
- Natural gas systems
- Stationary combustion
- Mobile combustion
- Abandoned underground coal mines

Figure 2.3 – Major Sources of Methane Emissions from the Energy Sector in California



2.1.1 – Petroleum Systems

Methane emissions from petroleum systems are mainly associated with the following activities:

- Crude oil production field operations
- Crude oil transportation
- Refining operation

Table 2.3 – Summary of Methane Emissions from Petroleum Systems in the USA

	USA (2004)	
Source	**MMT$_{CO2\text{-}Eq.}$**	**(%)**
Production Field Operations	25	97.3%
Crude Oil Transportation	0.1	0.4%
Refining Operation	0.6	2.3%
Total	**25.7**	100%

Out of the 25.7 MMT$_{CO2\text{-}Eq.}$ methane emissions from petroleum systems in the United States in 2004, production field operations account for 97%; followed by 2% in refining operations, and less than one percent in crude oil transportation (see Table 2.3). The relative contribution of each sub-sector within the petroleum systems in California should be similar to the corresponding ones in the United States. The methane emissions from petroleum systems in California were 0.5 MMT$_{CO2\text{-}Eq.}$ in 2004, which is 1.8% of the state's total CH_4 emissions, 27.8 MMT$_{CO2\text{-}Eq.}$ (see Table 2.1). The relatively low contribution of the petroleum systems to the total methane emission can be partly attributed to the fact that many of the petroleum field operations in California are actually combined oil and natural gas systems (called "associated" fields). It is not really possible to distinguish emissions as being from just petroleum operations. Because many of California's operations are associated fields, it was referred to as "Petroleum & Natural Gas" Supply System in the California Emission Inventory Report; where components that could be associated with natural gas (such as gas cleanup) were referred to as "Natural Gas" Supply System (Church, 2007).

2.1.1.A – Production Field Operations

As mentioned, petroleum production field operations account for the majority, approximately 97%, of CH_4 emissions from the petroleum systems. The sources of methane emissions include (USEPA, 2006a):

- Pneumatic device venting
- Tank venting
- Combustion and process upsets
- Miscellaneous venting and fugitive emissions
- Wellhead fugitive emissions

The measures to reduce methane emissions from the petroleum systems (as well as natural gas systems to be discussed in Section 2.1.2) can be grouped into the following mitigation strategies that also apply to natural gas systems (Hendriks & de Jager, 2001):

- Prevention – improved process efficiencies and leakage reduction
- Recovery and re-injection – recovery of off-gases and re-injection into the subsystems such as oil reservoirs and natural gas transport pipeline
- Recovery and utilization – recovery and utilization of otherwise emitted gases for energy production
- Recovery and incineration – recovery, followed by incineration (flaring) without energy production

Specific technological options to reduce CH_4 emissions from petroleum production field operations include the following:

- Flaring instead of venting – With regards to CH_4 emission reduction, flaring is a better alternative to venting because it destroys the gas rather than releasing it into the atmosphere and flaring converts methane to carbon dioxide which has a much lower GWP (USEPA, 2004; Hendriks & de Jager, 2001).
- Associated gas (vented) mix with other options – Instead of venting, emissions can be reduced by using the associated gas for consumption on the platform, and/or using the gas for domestic consumption by converting it to liquefied natural gas or to electricity (USEPA, 2004; IEA, 2003).
- Associated gas (flared) mix with other options – Instead of flaring, emissions can be reduced by using the associated gas for re-injection into the field for enhanced oil recovery, or for consumption within the facility (USEPA, 2004; IEA, 2003).
- Option for flared gas – Based on information reported by CARB (2005), flare use is responsible for approximately 13% of CH_4 emissions from the petroleum sector in California. Implementation of techniques, such as optimization of flare burner pressure drop and exit

velocities, could enhance the overall efficiencies of flaring from 90 to 99%, an additional 10% oxidation of CH_4 fed to the flare (CEC, 2005).

Table 2.4 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from production field operations in petroleum systems. It should be noted here that all the values in this table and the other similar tables in this report with regards to lifetime, market penetration, reduction efficiency, technical applicability, and costs of technological options were directly extracted from the literature search; factors, such as new regulations, development of the technologies, economic conditions, may affect these projected values. In addition, assessment of the current status of these technological options is beyond the scope of work of this project.

Table 2.4 – Technological Options for Petroleum Systems – Production Field Operations

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Flaring instead of venting[1]	15	100	98	5	\$33.30	\$1.00	\$0.00
Associated gas (vented) mix with other options[1]	15	100	90	23-25	\$69.54	\$1.11	\$3.71
Associated gas (flared) mix with other options[1]	15	100	95	14-15	\$66.61	\$2.21	\$3.71
Option for flared gas (improved flaring efficiencies)[2]	15	100	10	13	\$66.61	\$2.21	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & IEA (2003); 2: CEC (2005) & EC (2001)

2.1.1.B – Crude Oil Transportation

Crude oil transportation only account for approximately 0.4% of total CH_4 emissions from the petroleum systems. The mitigation options are very similar to those of the natural gas transmission. To avoid duplication, the mitigation options will be described along with those for the natural gas systems in the next section.

2.1.1.C – Refining Operations

Crude oil refining operations only account for approximately 2% of total CH_4 emissions from the petroleum systems. The relatively low percentage is because most of the methane gas in crude oil has been removed or escaped before the crude oil is delivered to refineries. The CH_4 emissions within refineries can be attributed to the following three sources (USEPA, 2006a):

- Vented emissions (87%)
    - Refinery system blow-down for maintenance
    - Process of asphalt blowing
- Fugitive emissions (6%)
    - Leaks in the fuel gas system
- Combustion emissions (7%)
    - Unburned methane in process heater stack emissions

  - Unburned methane in engine exhausts and flares

The CH_4 emissions from crude oil transportation and refining operations are relatively small, and their mitigation options are very similar to those of the natural gas processing and transmission. To avoid duplication, their mitigation options will be described along with those for the natural gas systems in the next section.

2.1.2 – Natural Gas Systems

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines (USEPA, 1999). Methane emissions from natural gas systems are mainly associated with the following activities:

- Field production
- Processing
- Transmission and storage
- Distribution

Out of the total 118.8 $MMT_{CO2\text{-}Eq.}$ methane emissions from natural gas systems in the United States in 2004, each of the four above-mentioned activities contributes significantly to methane emissions (see Table 2.5). The relative contribution of each sub-sector within the natural gas systems in California should be similar to its corresponding part in the USA. The methane emissions from natural gas systems in California were 1.4 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 5.0% of the state's total methane emissions, 27.8 $MMT_{CO2\text{-}Eq.}$ (see Table 2.1).

Table 2.5 – Summary of Methane Emissions from Natural Gas Systems in the USA

	USA (2004)	
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**
Field Production	39.3	33.1%
Processing	14.0	11.8%
Transmission and Storage	38.4	32.3%
Distribution	27.1	22.8%
Total	**118.8**	**100%**

2.1.2.A – Field Production

In this initial stage of natural gas systems, gas wells are used to extract raw gas from subsurface formations. Sources of emissions include (USEPA, 2006a):

- Wells themselves
- Collection pipelines
- Well-site gas treatment facilities such as dehydrators and separators
- Fugitive emissions and emissions from pneumatic devices

- Emissions from routine maintenance and repair of wells and equipment

In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. They have identified many Best Management Practices (BMPs) that are cost-effective in reducing methane emissions (http://www.epa.gov/gasstar/techprac.htm). The program has sponsored a series of Lessons Learned Studies of these BMPs and several other practices. In addition, companies that are Natural Gas Star Partners have identified other practices, referred to as Partner-Reported Opportunities (PROs) that also reduce methane emissions (USEPA, 1999). Since 1990, the oil and gas industry in the United States has achieved over 10 billion cubic meters of methane emission reduction (Fernandez *et al.*, 2004).

Similar to the petroleum sector, the measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001). Specific technological options to reduce CH_4 emissions from natural gas field operations include the following:

- Good housekeeping practices to reduce blowouts – Improved equipment, procedures, and training of personnel would reduce the risks of blowout during exploration (de Jager *et al.*, 2001).
- Good operational procedures with regards to well-testing – Operational procedures can be optimized to minimize gas flow and duration of the tests during exploration. In the Netherlands, procedures have been tightened and the duration of a test is limited to 20 to 70 hours (de Jager *et al.*, 2001).
- Flaring of gas produced at well tests (during exploration) – Mobile flare installations can be used for this purpose to reduce methane emissions (de Jager *et al.*, 2001).
- Green completion – The common practice in gas well completion is to flare or vent initial produced gas. An alternative is to bring potable equipment to the well site that cleans up the initial produced gas to pipeline sales standard (Fernandez *et al.*, 2005).
- Install plunger-lift systems in gas wells – Venting is one of the traditional remedial operations for well blockage due to fluid accumulation. A plunger lift uses the natural energy of the well itself to lift the fluids out of the well to prevent well blockage. It will help maintain the production level and reduce methane emissions resulted from venting (USEPA, 2004; IEA 2003).
- Use surge vessels for station/well venting – During production, a surge vessel can be used to enable gas emitted during blow-downs to be recaptured for reuse as fuel or re-injection into the pipeline (USEPA, 2004; IEA, 2003).
- Replace high-bleed pneumatic devices with low-bleed pneumatic devices – During production, high-bleed pneumatic devices (powered by natural gas) will emit a high volume of CH_4 to the atmosphere (USEPA, 2004; IEA, 2003). Field experience shows that up to 80% of all high-bleed devices can be replaced with low-bleed devices that emit much lower volumes of CH_4 (Tingley & Fernandez, 2003).
- Replace high-bleed pneumatic devices with compressed-air systems – Replacing of the high-bleed pneumatic devices (powered by natural gas) with compressed air systems will completely eliminate CH_4 emissions from these pneumatic devices in the natural gas

production sector (USEPA, 2004; IEA, 2003). This is applicable at facilities with available electric power (Tingley & Fernandez, 2003). It should be noted that this option will incur some electricity-generation GHG emission.

- Reducing the glycol circulation rates in dehydrators – During natural gas production, tri-ethylene glycol (TEG) is circulated through dehydrators to absorb and remove water from the gas stream before the gas enters the transmission pipeline. TEG also absorbs some CH_4 that is vented. Reducing the TEG circulation rate to an optimal level will reduce CH_4 emissions (USEPA, 2004; IEA, 2003).
- Installation of flash tank separators on dehydrators – A flash tank separator is used, by reducing the pressure of methane-rich TEG suddenly to cause the absorbed methane to flash (vaporize). The flashed methane can be collected and used as fuel gas or compressed and returned to the sales line (USEPA, 2004; IEA, 2003).
- Replace glycol dehydrators with desiccant dehydrators – Desiccant dehydrators can be a good alternative to TEG systems. They are more suitable for high volume of gas to be processed with low temperature and high gas pressure. They produce methane emissions only when they are being refilled with desiccant, and even then the emissions are far lower than the TEG systems (Tingley & Fernandez, 2003).
- Minimizing strip gas in glycol dehydration – Natural gas is used as a strip-gas in the glycol regenerator. Methane emissions from strip gas can be minimized by reducing the amount of strip gas used, increasing the temperature at which the glycol is regenerated, and/or using alternative stripping gases such as nitrogen or off-gases from the condensate separation process (Hendriks & de Jager, 2001).
- Increasing the pressure of the condensate flash – This option reduces the amount of methane that is desorbed from the condensate. The reduction potential, however, will generally be limited (Hendriks & de Jager, 2001).
- Reroute glycol dehydrator vapor to vapor-recovery unit – Rerouting the vapor, instead of venting, from the glycol dehydrator to a vapor-recovery unit will reduce methane emission (Fernandez *et al.*, 2005).
- Reduction of purge gas streams – Purge gas is normally used in vent and flare systems to prevent air from entering the system. As the amount used is often unnecessarily high, reduction in methane emissions can be achieved by reducing the amount of purge gas used in this operation (Hendriks & de Jager, 2001).
- Portable evacuation compressor for pipeline venting – This option uses pump-down techniques to lower the pressure in the gas-line before venting in the natural gas production sector. An in-line portable compressor can be used to lower the line pressure by up to 90% of its original value without venting (USEPA, 2004; IEA, 2003).
- Fuel gas line retrofit for blow-down valve and alter emergency shutdown (ESD) practices – When a system is depressurized, emissions can result from “blow-down” (i.e., venting of the high-pressure gas left within the system). This option allows methane that would be vented when compressors are taken off-line to be re-routed to the fuel gas system (USEPA, 2004; IEA, 2003). Relocating valves closer to the compressor can reduce the volume of gas release during depressurizing at changeover or routine maintenance (Hendriks & de Jager, 2001). Modifying the emergency shutdown (ESD) vents and blowdown piping enables collection and rerouting of the gas to the sales line, the fuel box, lower pressure mains for non-emergency use, or flare systems (USEPA, 2004).

- Installation of electric starters on compressors – Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions (USEPA, 2004; IEA, 2003).
- Replace gas starters with air/nitrogen – Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions. Replacing natural gas with air will completely eliminate the venting of methane (Fernandez *et al.*, 2005). It can also be replaced with nitrogen (USEPA, 2004).
- Replace ignition/reduce false starts – Before starting a compressor, the discharge header is unloaded by venting gas to the atmosphere. The engine is then turned over, often using a gas-expansion turbine starter. Both operations vent methane to atmosphere. Replacing old point-contact ignition systems with newer electronic designs can reduce false starts and eliminate methane emissions (Fernandez *et al.*, 2005).
- Automate air/fuel ratio control – Natural gas-fueled internal combustion engines can provide continuous duty operations over a set range of air to fuel ratios (AFR). Fuel-rich conditions result in greater unburned fuel emissions (primarily methane) and higher CO emissions. Fuel savings and reduced associated emissions can be achieved by installing an automated AFR control system (USEPA, 2004).
- Replace the frequency of gas start with gas – Internal combustion engine driven turbine compressors are often started by directing un-ignited pipeline gas through the turbine compressor, rolling the turbine engine prior to ignition. The un-ignited gas, or startup natural gas, is vented to the atmosphere. Operating and maintenance schedules dictate how frequently such turbine engines are restarted. Modifying maintenance practices and operational schedule can reduce emissions (USEPA, 2004).
- Inspection and maintenance (pipeline leaks) – This directed inspection and maintenance option is to survey pipelines in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (equipment and facilities) – This directed inspection and maintenance option is to survey facilities and equipment in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (chemical inspection pumps) – This directed inspection and maintenance option is to survey chemical inspection pumps in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (enhanced) – This option is a more aggressive inspection and maintenance program with increasing frequency to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Table 2.6 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from production activities in natural gas systems.

Table 2.6 – Technological Options for Natural Gas System – Production

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Installation of plunger lift systems in gas wells[1]	10	100	4	1	\$3,986	\$159.42	\$8.21
Surge vessels for station/well venting[1]	10	100	50	<1	\$11,216	\$224.52	\$8.53
Replace high-bleed with low-bleed pneumatic devices[1]	5	50	86	8	\$14.01	\$0.00	\$8.21
Replace high-bleed pneumatic devices with compressed air systems[1]	5	50	100	8	\$6.82	\$62.06	\$8.21
Reducing glycol circulation rates in dehydrators[1]	1	50	31	1	\$0.00	\$1.72	\$8.21
Installation of flash tank separators[1]	5	50	54	3	\$100.98	\$0.00	\$8.21
Installation of electric starters on compressors[2]	10	-	75	<0.5	\$838.62	\$2,096	\$6.82
Portable evacuation compressor for pipeline venting[1]	15	100	72	<1	\$318.58	\$2.28	\$8.52
Inspection and maintenance (pipeline leaks)[1]	5	100	60	2	\$22.78	\$34.18	\$8.21
Inspection and maintenance (facilities & equipment)[2]	5	-	33	1-3	\$193.25	\$289.88	\$6.82
Inspection and maintenance (chemical inspection pumps)[2]	5	-	40	1-2	\$123.14	\$6.82	\$6.82
Inspection and maintenance (enhanced)[2]	5	-	50	0-1	\$246.40	\$344.96	\$6.82

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005); 2: IEA (2003) & USEPA (2004)

2.1.2.B – Processing

Subsequent to field production, "impurities" such as natural gas liquids and various other constituents from the extracted raw gas are removed, resulted in "pipeline quality" gas that is injected into transmission pipe and storage system. Fugitive emissions from compressors, including compressor seals are the primary emission source (USEPA, 2006a).

The mitigation options for methane emission during processing of natural gas are very similar to those for transmission and storage, so they will be described next in Section 2.1.2.C.

2.1.2.C – Transmission and Storage

Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include (USEPA, 2006a):

- Fugitive emissions from the compressor stations
- Fugitive emission from metering and regulating stations
- Pneumatic devices
- Engine exhaust in compressor stations
- Compressors and dehydrators in storage facilities

Specific technological options to reduce CH_4 emissions from natural gas processing and transmission include the following:

- Using hydraulically-powered valve actuators (compressors) – Valve actuators are typically powered by natural gas, which is released during the valve movement. They can be replaced with locally-mounted hydraulic actuator systems and methane emissions from this source will be eliminated (Hendriks & de Jager, 2001).
- Recompression of gas during maintenance (compressors) – Emissions can be reduced through recompression of emissions during maintenance by using a portable compressor unit and re-routing them back to the system (Hendriks & de Jager, 2001).
- Fuel gas line retrofit for blow-down valve and alter emergency shutdown (ESD) practices (compressors) – When a system is depressurized, emissions can result from “blow-down” (i.e., venting of the high-pressure gas left within the system). This option allows methane that would be vented when compressors are taken off-line to be re-routed to the fuel gas system (USEPA, 2004; IEA, 2003). Relocating valves closer to the compressor can reduce the volume of gas release during depressurizing at changeover or routine maintenance (Hendriks & de Jager, 2001). Modifying the emergency shutdown (ESD) vents and blowdown piping enables collection and re-routing of the gas to the sales line, the fuel box, lower pressure mains for non-emergency use, or flare systems (USEPA, 2004).
- Reduced flushing of engines at start-up and shut-down (compressors) – It has been reported from investigation of several gas-transporting companies that flushing compressors or engines before start-up is not required. Formation of an explosive mixture is prevented by the overpressure in the system (Hendriks & de Jager, 2001).
- Alter start-up procedure during maintenance (compressors) – Instead of shutting down compressors during monthly cleaning maintenance, deionized water is sprayed into the compressors while the compressors are still on-line (running). This procedure can reduce the required number of compressor start-ups/depressurizations per year (USEPA, 2004; IEA, 2003).
- Reciprocating compressor rod packing (Static-Pac) – Use Static-Pac® seal or Emissions Packing System® to reduce fugitive losses from compressors when they are placed in the standby mode. An automatic controller activates when the compressor is shutdown to wedge a tight seal around the shaft (USEPA, 2004). Use of Seal Assist System® allows compressor rod seal leaks to be captured and used to fuel IC engine at the compressor station (IEA, 2001)
- Replace wet seals with dry seals on centrifugal compressors – Some centrifugal compressors are fitted with wet seals that circulate oil at the seal face to prevent gas emissions. Dry seals

use high-pressure gas to ensure sealing and emit much less methane in comparison to the wet-seal systems (USEPA, 2004; IEA, 2003).

- Use surge vessels for station/well venting – During processing and transmission, a surge vessel can be used to enable gas emitted during blow-downs to be recaptured for reuse as fuel or re-injection into the pipeline (USEPA, 2004; IEA, 2003).
- Replace high-bleed pneumatic devices with low-bleed pneumatic devices – During processing and transmission, high-bleed pneumatic devices (powered by natural gas) will emit a high volume of CH_4 to the atmosphere. These devices can be replaced with low-bleed devices that emit much lower volumes of CH_4 (USEPA, 2004; IEA, 2003).
- Replace high-bleed pneumatic devices with compressed-air systems – Replacing the high-bleed pneumatic devices (powered by natural gas) with compressed air systems will completely eliminate CH_4 emissions from these pneumatic devices in the processing and transmission sectors (USEPA, 2004; IEA, 2003).
- Reducing the glycol circulation rates in dehydrators – During natural gas processing and transmission, tri-ethylene glycol (TEG) is circulated through dehydrators to absorb and remove water from the gas stream before the gas enters the transmission pipeline. TEG also absorbs some CH_4 that is vented. Reducing the TEG circulation rate to an optimal level will reduce CH_4 emissions (USEPA, 2004; IEA, 2003).
- Installation of flash tank separators on dehydrators – A flash tank separator is used, by reducing the pressure of methane-rich TEG suddenly to cause the absorbed methane to flash (vaporize). The flashed methane can be collected and used as fuel gas, or compressed and returned to the sales line in the processing and transmission sectors (USEPA, 2004; IEA, 2003).
- Replacement of reciprocating engines by gas turbines – This option replaces natural gas reciprocating engines with natural gas turbines. The turbines have a better combustion efficiency than gas turbine, and, thus, methane emissions are reduced (USEPA, 2004; IEA, 2003).
- Catalytic converter – A catalytic converter can be used as an after-burner to reduce methane emissions resulting from incomplete combustion (USEPA, 2004; IEA, 2003).
- Portable evacuation compressor for pipeline venting – This option uses pump-down techniques to lower the pressure in the gas-line before venting. An in-line portable compressor is used to lower the line pressure by up to 90% of its original value without venting (USEPA, 2004; IEA, 2003).
- Composite wrap to repair non-leaking pipeline defects – The traditional method for rehabilitating a failed pipe is by cut-and-weld. Recently many gas companies have started wrapping a composite sleeve around the existing pipe. For many defects, this technique is less expensive and avoids the need for purging the pipeline to the atmosphere (Tingley & Fernandez, 2003).
- Installation of electric starters on compressors – Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions (USEPA, 2004; IEA, 2003).
- Replace gas starters with air/nitrogen – Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the

engine, but use of them results in methane emissions. Replacing natural gas with air will completely eliminate the venting of methane (Fernandez *et al.*, 2005). It can also be replaced with nitrogen (USEPA, 2004).

- Replace ignition/reduce false starts – Before starting a compressor, the discharge header is unloaded by venting gas to the atmosphere. The engine is then turned over, often using a gas-expansion turbine starter. Both operations vent methane to atmosphere. Replacing old point-contact ignition systems with newer electronic designs can reduce false starts and eliminate methane emissions (Fernandez *et al.*, 2005).
- Automate air/fuel ratio control – Natural gas-fueled internal combustion engines can provide continuous duty operations over a set range of air to fuel ratios (AFR). Fuel-rich conditions result in greater unburned fuel emissions (primarily methane), higher CO emissions. Fuel savings and reduced associated emissions can be achieved by installing an automated AFR control system (USEPA, 2004).
- Replace the frequency of gas start with gas – Internal combustion engine driven turbine compressors are often started by directing un-ignited pipeline gas through the turbine compressor, rolling the turbine engine prior to ignition. The un-ignited gas, or startup natural gas, is vented to the atmosphere. Operating and maintenance schedules dictate how frequently such turbine engines are restarted. Modifying maintenance practices and operational schedule can reduce emissions (USEPA, 2004).
- Automate system operation to reduce venting – Transmission pipelines often have multiple compressor stations with five to ten compressors at each station. Where these compressors have older ignition systems, shutdowns and restarts result in blowdown and gas pneumatic starter emissions that release excessive amounts of methane to the atmosphere. Employing automatic control systems on compressor ignition systems can effectively increase the operational efficiency and reliability of the compressor and also reduce methane emissions (USEPA, 2004).
- Replace compressor cylinder unloaders – Compressor cylinder unloaders are used to 1) reduce the machine's start-up load, 2) prevent an overload when there is an upset in operating conditions, and 3) control gas volumes due to fluctuations in rate requirements. Many older reciprocating engine-powered compressors are equipped with outdated or worn cylinder unloaders that continuously leak natural gas even when regularly maintained. Replacing the cylinder unloaders with a design that utilizes a balanced piston that avoids chatter and minimizes the pressure required for operation can reduce emissions (USEPA, 2004).
- Inspection and maintenance (pipeline leaks in transmission) – This directed inspection and maintenance option is to survey pipelines in the transmission sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (compressor stations) – This directed inspection and maintenance option is to survey compressor stations in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (compressor stations - enhanced) – This option is a more aggressive inspection and maintenance program with increasing frequency to survey compressor stations in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

- Inspection and maintenance (storage wells) – This directed inspection and maintenance option is to survey storage wells in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (storage wells - enhanced) – This option is a more aggressive inspection and maintenance program with increasing frequency to survey storage wells in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Table 2.7 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from processing and transmission activities in natural gas systems.

2.1.2.D – Distribution

Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

Specific technological options to reduce CH_4 emissions from natural gas distribution include the following:

- Electronic monitoring at large surface facilities – To ensure that both peak and non-peak operating pressures are met; natural gas distribution systems typically operate at gas pressures that are higher than necessary. Use of electronic monitoring can match the distribution system pressure with real time demand and, thus, reduce methane emission (USEPA, 2004; IEA, 2003).
- Replacement of cast-iron/unprotected steel pipeline – Cast iron and unprotected steel pipeline are prone to corrosion and leaks. They should be replaced with non-corrosive materials that will reduce methane losses from the distribution system (USEPA, 2004; IEA, 2003).
- Replacement of unprotected steel services – Unprotected steel services are prone to corrosion and leaks. They should be replaced with non-corrosive materials, such as plastic or protected services, that will reduce methane losses from the distribution system (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (pipeline leaks) – This directed inspection and maintenance option is to survey pipelines at the distribution facilities to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).
- Inspection and maintenance (enhanced) – This option is a more aggressive inspection and maintenance program with increasing frequency at the distribution facilities to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).
- Gas conditioning – Within the low-pressure network, conditioning gas with mono-ethylene glycol to swell the yarn within the joints of the grey cast-iron mains may reduce leakage. However, glycol may have an adverse effect on the new plastic lines, the control systems, and domestic gas equipment (Hendriks & de Jager, 2001).

Table 2.7 – Technological Options for Natural Gas System – Processing and Transmission

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Surge vessels for station/well venting[1]	10	100	50	3	$11,216	$224.52	$8.53
Replace high-bleed with low-bleed pneumatic devices[1]	5	50	86	4	$14.01	$0.00	$8.21
Replace high-bleed pneumatic devices with compressed air systems[1]	5	50	100	4	$7.09	$62.06	$8.21
Reducing glycol circulation rates in dehydrators[1]	1	50	30	<1	$0.00	$0.87	$8.53
Installation of flash tank separators[1]	5	50	61	<1	$32.59	$0.00	$8.53
Replace reciprocating engines with gas turbines[2]	20	-	90	0-27	$166.52	$8.30	$0.00
Reciprocating compressor rod packing (Static-Pac)[1]	1	100	21	6	$14.58	$0.56	$8.53
Replace wet seals with dry seals on centrifugal compressors[2]	5	-	69	4-6	$96.68	-$25.38	$6.99
Alternating start-up procedure during maintenance[1]	1	100	100	3	$0.00	$0.00	$4.47
Catalytic converter[2]	10	-	56	5-8	$91.46	$4.82	$0.00
Fuel gas retrofit for blow-down valve[1]	5	100	33	21	$1.94	$0.00	$8.47
Portable evacuation compressor for pipeline venting[1]	15	100	72	3	$318.58	$2.28	$8.52
Inspection and maintenance (pipeline leaks in transmission)[1]	5	100	60	<1	$786.60	$1,180	$8.53
Inspection and maintenance (compressor stations)[1]	5	100	13	4	$0.57	$1.86	$8.53
Inspection and maintenance (compressor stations - enhanced)[2]	5	-	20	2-4	$0.40	$2.43	$7.08
Inspection and maintenance (storage wells)[1]	5	100	33	<1	$38.50	$38.50	$8.53
Inspection and maintenance (storage wells - enhanced)[2]	5	-	50	<0.5	$38.59	$38.59	$7.08

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{\text{CO2-Eq.}}$

1: USEPA (2004) & CEC (2005); 2: IEA (2003) & USEPA (2004)

Table 2.8 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from distribution activities in natural gas systems.

Table 2.8 – Technological Options for Natural Gas System – Distribution

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Electronic monitoring at large surface facilities[1]	5	100	95	6	$28.07	$4.68	$11.37
Replacement of cast iron/unprotected steel pipeline[2]	5	-	95	6-10	$17,259	$0.86	$9.74
Replacement unprotected steel services[2]	5	-	95	3-4	$410,830	$82.17	$9.74
Inspection and maintenance (pipeline leaks)[1]	5	100	26	9	$4.88	$5.76	$11.30
Inspection and maintenance (enhanced)[2]	5	-	66	1-12	$21.14	$21.08	$9.42

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005); 2: IEA (2003) & USEPA (2004)

2.1.3 – Stationary Combustion

Stationary combustion includes all fuel combustion activities from fixed sources (versus mobile combustion). For stationary sources, methane may result from incomplete combustion of fuels. The *IPCC Guidelines* categorize emissions of NCGGs from stationary combustion-related activities into five sectors (IPCC, 1997):

- Energy industries (electricity generation, charcoal production, etc.)
- Manufacturing industries
- Commercial/institutional sector
- Residential Sector
- Stationary agriculture/forestry/fishing sources

Methane is produced in small quantities from fuel combustion due to incomplete combustion of hydrocarbons in fuel. The production of CH_4 is a function of the temperature in the boiler/kiln/stove. In large facilities and industrial applications, the combustion is more efficient and the emission rate is very low. On the other hand, emission rates from smaller combustion sources are often higher, particularly when smoldering occurs. The highest rates of CH_4 emissions from fuel combustion occur in residential applications such as small stoves and open burning (USEPA, 2006a).

Fuel type (coal, fuel oil, natural gas, or wood) and characteristics (including the calorific value), type of technology (including the combustion, operating and maintenance regime, size and vintage of the equipment), and emission controls, are major factors determining rates of methane gas emissions from stationary sources. Moisture content, carbon fraction, and combustion efficiencies are also important factors to consider (USEPA, 2006a).

In addition to electricity combustion, industrial stationary sources for methane emissions include gasoline and diesel used in various equipment (manufacturing and industrial sectors, food and agricultural processing, off-road equipment, ships and commercial boats, and trains). Commercial stationary sources for methane emissions include diesel and liquefied gas used in asphalt paving and roofing, commercial lawn and garden equipment, and others. They also include natural gas emissions from commercial water and space heating, cooking, and commercial off-road equipment (CEC, 2006).

The methane emissions from stationary combustion in California were 1.3 $\mathrm{MMT_{CO2\text{-}Eq.}}$ in 2004, which is 4.7% of the state's total methane emissions, 27.8 $\mathrm{MMT_{CO2\text{-}Eq.}}$ (see Table 2.1).

Little information regarding technological options for methane emission reduction in this sector was found from the literature search. Basically, reducing energy demand and improving combustion efficiency can reduce methane emissions from this sector.

2.1.4 – Mobile Combustion

Methane emissions from mobile sources depend on methane content of the motor fuel, the amount of hydrocarbons remained un-burned in the engine exhaust, the engine type, and post-combustion controls. In vehicles without emission controls, the amount of CH_4 emitted is highest at low speeds and when the engine is idle. Poorly tuned engines would have higher CH_4 emissions (USEPA, 2006a).

Emissions from mobile combustion are often grouped by transport mode (e.g., highway, air, rail), fuel type (e.g., motor gasoline, diesel fuel, jet fuel), and vehicle type (e.g., passenger cars, light-duty trucks). Road transport accounted for most of the mobile source fuel consumption, and, consequently, the majority of mobile combustion emissions (see Table 2.9). Mobile combustion was responsible for a very small portion of methane emissions (0.5%) in the United States. Due to the control technologies employed on highway vehicles that reduce CO, NO_x, VOC, and methane emissions, methane emissions from mobile combustion have declined 38% from 1990 to 2.9 $\mathrm{MMT_{CO2\text{-}Eq.}}$ in 2004 (USEPA, 2006a).

The methane emissions from the mobile sources in California were 0.6 $\mathrm{MMT_{CO2\text{-}Eq.}}$ in 2004, which is 2.2% of the state's total methane emissions, 27.8 $\mathrm{MMT_{CO2\text{-}Eq.}}$ (see Table 2.1)

Little information regarding technological options for methane emission reduction in this sector was found from the literature search. Basically, using alternative fuels, reducing travel, and improving vehicle efficiency can reduce methane emissions from this sector (CARB, 2004).

Table 2.9 – Summary of Methane Emissions from Mobile Source in the USA

	USA (2004)	
Source	**MMT$_{CO2-Eq.}$**	**(%)**
Gasoline Highway	**2.2**	**75.9%**
Passenger Cars	1.3	
Light-Duty Trucks	0.9	
Heavy-Duty Vehicles	0.1	
Motorcycles	<0.05	
Diesel Highway	**<0.05**	**~0%**
Passenger Cars	<0.05	
Light-Duty Trucks	<0.05	
Heavy-Duty Vehicles	<0.05	
Alternative Fuel Highway	**0.1**	**3.4%**
Non-Highway	**0.6**	**20.7%**
Ships and Boats	0.1	
Locomotives	0.1	
Farm Equipment	0.1	
Construction Equipment	0.1	
Aircraft	0.1	
Other	0.1	
Total	**2.9**	**100%**

2.1.5 – Abandoned Underground Coal Mines

Active underground coal mines contribute a large share of methane emissions in the United States. As mines mature and coal seams are mined through, mines will be closed and abandoned. Many abandoned mines were sealed and some were flooded through groundwater intrusion or by surface water. Some abandoned coal mines are vented to the atmosphere to prevent the buildup of methane gas. After an initial decline, abandoned coal mines can liberate methane gas at a steady-state rate for a long period of time. The following factors influence methane emissions from abandoned coal mines (USEPA, 2006a):

- Time since abandonment
- Gas content and adsorption characteristics of coal
- Methane flow capacity of the mine
- Mine flooding
- Presence of vent holes
- Mine seals

Although there are no active coal mines in California, there were coal-mining activities in the past. Methane emissions from abandoned coal mines were not included in the most recent inventory report by CEC (CEC, 2006). Flaring of the collected off-gases is a viable option to reduce methane emissions from abandoned underground coal mines.

2.2 – Industrial Processes

Out of the twenty industries that may have GHG emissions, petrochemical production is the only industrial process that may have sizable methane emissions in California.

Petrochemicals are chemicals isolated or derived from petroleum or natural gas. During the production of some petrochemicals, small amounts of methane may be released. The potential sources of methane emissions are from the production of (USEPA, 2006a):

- Carbon black
- Ethylene
- Ethylene dichloride
- Styrene
- Methanol

Methane emissions from petrochemical production in the United States in 2004 were 1.6 $MMT_{CO2\text{-}Eq.}$, increased 7% from 2003 and 38% since 1990. Although production of these petrochemicals is occurring in California, methane emissions from petrochemical production were not included in the most recent report by CEC (CEC, 2006). Flaring of the collected off-gases is a viable option to reduce methane emissions from this industrial sector.

2.3 - Agriculture

Agricultural activities currently generate the largest share of anthropogenic methane emissions both in California and the United States. Methane emissions from agricultural activities can be grouped into the following categories:

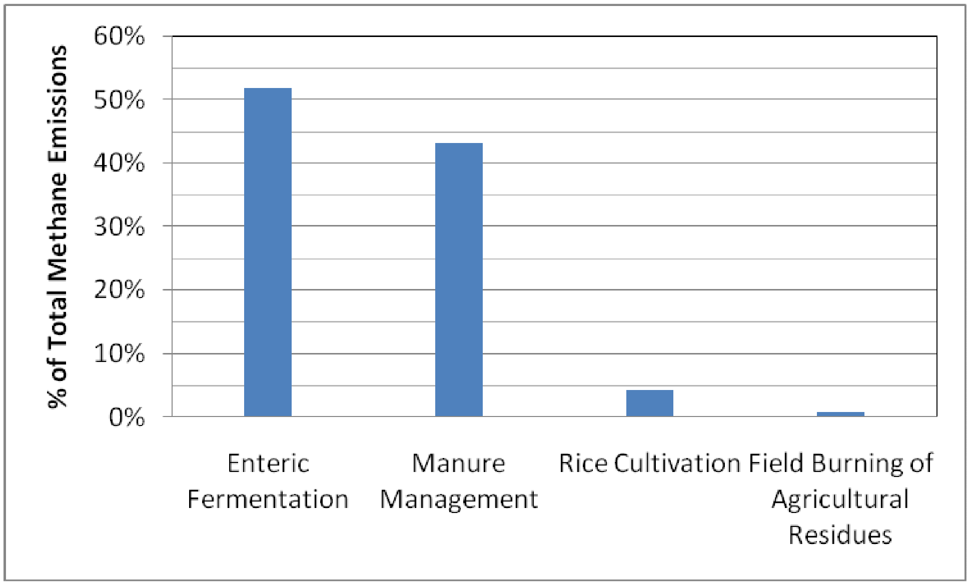
- Enteric fermentation
- Manure management
- Rice cultivation
- Field burning of agricultural residues

Table 2.10 summarizes the methane emissions from the agriculture sector in California and in the United States. The data were extracted from the recent inventory reports of USEPA and CEC (USEPA, 2006; CEC 2006). Enteric fermentation and manure management are the two dominant methane emission sources in agriculture sector, followed by rice cultivation. The methane emissions from the agriculture sector in California were 13.9 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 50% of the state's total methane emissions, 27.8 $MMT_{CO2\text{-}Eq.}$ (see Table 2.1). The top contributors for the CH_4 emissions from the agricultural sector in California, in the order of magnitude are enteric fermentation (51.8%), manure management (43.2%), rice cultivation (4.3%), and field burning of agriculture residues (0.7%). Enteric fermentation and manure management: each is responsible for almost half of the total methane emission from the agricultural sector in California. Figure 2.4 plots the major sources of methane emissions from the agriculture sector in California in a descending order.

Table 2.10 – Summary of Methane Emissions from the Agriculture Sector in the USA and CA

	USA (2004)		California (2004)		
Source	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Enteric Fermentation	112.6	70.2%	7.2	51.8%	6.4%
Manure Management	39.4	24.5%	6.0	43.2%	15.2%
Rice Cultivation	7.6	4.7%	0.6	4.3%	7.9%
Field Burning of Agricultural Residues	0.9	0.6%	0.1	0.7%	11.1%
Total	**160.5**	100%	**13.9**	100%	**8.7%**

Figure 2.4 – Major Sources of Methane Emissions from Agriculture Sector in California



2.3.1 – Enteric Fermentation

Methane is produced as part of the normal digestive processes in animals. During digestion, microorganisms in the digestive system ferment the ingested feed. This enteric fermentation process produces methane as a by-product, which can be eructed by the animal through the mouth or gut. The amount of methane produced and excreted by an individual animal depends mainly on the animal's digestive system and on the amount and type of food it consumes.

Because of their unique digestive system, ruminant domestic animals (e.g., cattle, sheep, and goats) are the major emitters of methane. Ruminant animals possess a rumen (a large "fore-stomach") in which microbial fermentation breaks down the ingested food into products that can be absorbed and metabolized. This microbial fermentation enables them to digest coarse plant material that non-ruminant animals cannot. Consequently, ruminant animals have the highest methane emission rates among all animal types. Non-ruminant domestic animals (e.g., swine, horses, and mules) also are methane emitters through enteric fermentation in the large intestine, but the per-animal methane emission rate of non-ruminants is less (USEPA, 2006a).

In addition to type of digestive system, methane emission rate from an animal depends on feed quality and intake rate. In general, lower feed quality and higher feed intake rate yield more methane emission. Feed intake rate is proportional to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work).

In the United States, beef cattle accounts for 71% of total livestock methane emissions in 2004, followed by 24% for dairy cattle, and the remaining 5% was from horses, sheep, swine, and goats (USEPA, 2006a). US EPA has voluntary Ruminant Livestock Efficiency Program underway as part of the Climate Change Action Plan toward emission reductions. The methane emissions from enteric fermentation in California were 7.2 $\text{MMT}_{\text{CO2-Eq.}}$ in 2004, which is 25.9% of the state's total methane emissions, 27.8 $\text{MMT}_{\text{CO2-Eq.}}$ (CEC, 2006). It should be noted here that there is some controversy regarding enteric emissions, but, generally, the numbers used in the CARB's inventory reflects the preferred methodology at this time (Church, 2007).

Methane production actually represents an economic loss to the farmers because feed is converted to methane rather than useful product. As much as 7% of an animal's feed can be lost as methane; therefore, there is an incentive for the farmers to minimize enteric fermentation (Branosky & Greenhalgh, 2007). Strategies to reduce methane emission enteric fermentation include (de Jager *et al.*, 2001; DeAngelo *et al.*, 2006):

- Reduction of livestock
- Increase of feed conversion efficiency by adjusting animal diets
- Increase of animal production through the use of growth hormones
- Increase of animal production by improved genetic characteristics
- Improve nutrition through strategic supplementation
- Improved reproduction

The key reduction options are changing animal diets and use of more productive animal types (Lucas *et al.*, 2006). Although many options have been mentioned, few studies include cost data for implementing mitigation options (DeAngelo *et al.*, 2006). Specific technological options to reduce methane emissions from enteric fermentation include the following:

- Livestock reduction – An effective measure in reducing animal methane emissions is a reduction in animal numbers. However, reduction of livestock will obviously have implications for farm profitability and for the size of the agricultural sector; it will also reduce the supply of farm product such as meat and milk (Bates, 2001). This is not an acceptable solution as a stand-alone option; however, it may be possible to reduce methane emissions by combining with improvements in animal efficiency with lower livestock numbers (O'Hara *et al.*, 2003).
- Improved feed conversion efficiency (improved level of feed intake) – An increase in level of feed intake can change the volatile fatty acid (VFA) content in the rumen and less acetate and more propionate is formed resulted in lower methane production and emissions (de Jager *et al.*, 2001).
- Improved feed conversion efficiency (replacing roughage with concentrates) – Roughage contains a high level of structural carbohydrates (fibers). Replacing part of the roughage in

the animal diet with concentrates can improve propionate generation and reduce methane production and emissions (Cole *et al*., 1996; Cole *et al*., 1997; de Jager *et al*., 2001).

- Improved feed conversion efficiency (changing composition of concentrates) – Adding unsaturated fatty acid and/or lipids (high fat diet) to the animal diet can increase the formation of propionate and reduce methane production and emissions (de Jager *et al*., 2001; Bates, 2001).
- Improved feed conversion efficiency (alkali/ammonia/urea treatment of low quality roughage) – The digestibility of low quality roughages such as straw can be improved by treatment using chemicals such as sodium hydroxide, ammonium hydroxide, and urea. Substantial methane reduction is feasible in combination with livestock reduction (de Jager *et al*., 2001; Bates, 2001).
- Improved feed conversion efficiency (chopping of low quality crop by-products) – Physical modifications of straws and other crop-by-product by chopping and milling can also improve feed intake and animal performance and result in less methane production and emissions (Cole *et al*., 1996; Cole *et al*., 1997; de Jager *et al*., 2001).
- Improved feed conversion efficiency (wrapping and preserving rice straw) – By wrapping freshly-cut and urea-treated straw in bales, its nutritive value can be better retained and spoilage is prevented (de Jager *et al*., 2001; Bates, 2001).
- Improving animal productivity through the use of growth hormones – Naturally occurring hormones and synthetic compounds have been identified or developed to achieve production-enhancing effects. Use of these hormone compounds reduce methane emissions through improved feed efficiency and reduced time to slaughter. Although the use of growth hormones is currently considered controversial, a large number of compounds such as recombinant bovine somatropin (rbST), antibiotics and anabolic steroids are currently being used and tested as feed additives for ruminants (de Jager *et al*., 2001; O'Hara *et al*., 2003; Bates, 2001).
- Improving genetic characteristics – Genetic manipulation of rumen bacteria and/or animals can potentially reduce methane emissions; however, ethical aspects and public acceptance are topics to be dealt with (Cole *et al*., 1996; de Jager *et al*., 2001).
- Improving nutrition through strategic supplementation (defaunation) – One way to manipulate the rumen microbial population is defaunation, in which all protozoa (typically 50% of the total microbial mass in rumen) are eliminated. Defaunation of the rumen has shown a 30 to 45% decrease in methanogenesis (de Jager *et al*., 2001).
- Improving nutrition through strategic supplementation (probiotics) – Probiotics are microbial feed additives that contain live cells and a growth medium. These can stimulate milk yield and increase weight gain (Bates, 2001; de Jager *et al*., 2001).
- Improving nutrition through strategic supplementation (antimethanogen) – Certain halogenated compounds such as chloroform, carbon tetrachloride, and methylene chloride can inhibit methane production up to 90%; however, they are not suitable as feed additives yet, because of the associated accumulation of hydrogen and their volatile characteristics (de Jager *et al*., 2001).
- Improving nutrition through strategic supplementation (molasses/urea blocks) – Many nutrients must be present in the diet to support the rumen microbial population; ammonia concentration in rumen is often the primary limitation on efficient digestion. Urea added to the diet has been the most effective method of boosting ammonia levels in the rumen. The

molasses/urea block (MUB) is easy to use and methane emission reductions per unit product can be as high as 40% (de Jager *et al.*, 2001).

- Improving nutrition through strategic supplementation (molasses/urea blocks with bypass protein) – Animals capable of higher yields and faster growth-rates need a greater supply of amino acids. Providing supplements of molasses/urea blocks (MUBs) with by-pass proteins, which can escape degradation in the rumen and are digested in the lower gut, can greatly increase milk yield and weight-gain of animals on straw/forage (de Jager *et al.*, 2001).
- Improving nutrition through strategic supplementation (targeted mineral/protein supplement) – Protein and specific minerals may be deficient seasonally or throughout the year. Supplements targeted to these deficiencies can improve productivity and reduce methane emissions (de Jager *et al.*, 2001).
- Improving reproduction – Many ruminants are maintained for purpose of producing offspring. By improving animals' reproductive efficiency, methane emissions per unit product can be reduced. The potential strategies include twinning, embryo transplantation, and artificial insemination, and estrus synchronization (de Jager *et al.*, 2001).
- Intensive grazing – In a management-intensive grazing system, cattle are frequently rotated between pastures to allow recently-grazed pastures time to regrow and to provide cattle with more nutritious pasture grazing. This option may reduce animal yield, but it will decrease methane emission by an even larger percentage (USEPA, 2006b).

2.3.2 – Manure Management

Livestock manure is another significant source of methane emission as a result of anaerobic decomposition of manure. When livestock or poultry manure is handled as a solid (e.g., in stacks or dry-lots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no methane gas. However, if manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid or slurry in lagoons, ponds, tanks, or pits), methane would be generated. Methane emission rates depend on ambient temperature, moisture, and manure storage/residence time. For large dairy and swine producers, use of liquid system is increasing. In addition, an increase of manure managed and stored on site at small dairies results from new regulations which limit the use of daily spread systems. Both practices increase the methane emissions from manure management unless methane gas is recovered from the digesters/lagoons (USEPA, 2006a).

Manure composition also affects the amount of methane production. The composition varies by type of animal's digestive system and diet. Generally speaking, the greater the feed's energy content, the greater the methane emission potential. For example, feedlot cattle fed with a high-energy grain diet generate manure with a high methane-producing capacity. Range cattle fed with a low-energy diet of forage material produce manure with approximately 50% of methane-producing potential of feedlot cattle manure. However, some higher energy feeds are more digestible and will result in less manure. Consequently, the quantity and characteristics of the manure depend on both the feed type and the growth rate of the animal (USEPA, 2006a). US EPA has the voluntary AgStar (livestock manure systems) program underway as part of the Climate Change Action Plan toward emission reductions (de la Chesnaye *et al.*, 2001).

In the United States, methane emissions from manure management in 2004 were 39.4 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$, 26% higher than that in 1990. The majority of this increase was from manure of swine and dairy cows. The increase in methane emissions from these animal types is primarily attributed to shifts towards large facilities in the swine and dairy industries. Although national dairy animal populations have been decreasing, some states, including California, have seen increases in their dairy populations as the industry becomes more concentrated in specific areas of the country. These areas of concentration tend to utilize more liquid systems to manage (flush or scrape) and store manure. Use of liquid manure management systems has higher methane emission potential than dry systems (USEPA, 2006a).

The methane emissions from manure management in California were 6.0 $\text{MMT}_{\text{CO2-Eq.}}$ in 2004, which is 21.6% of the state's total methane emissions, 27.8 $\text{MMT}_{\text{CO2-Eq.}}$ (see Table 2.1).

In general, measures to mitigate methane emissions from manure management include livestock reduction, prevention of fermentation during stabling, controlled fermentation of manure, composting, and aerobic digestion. The key reduction option is the capture and use of methane emissions through the use of anaerobic digesters that can be farm scale or centralized for the intensive agricultural zones (Lucas *et al.*, 2006). Specific technological options to reduce CH_4 emissions from manure management include the following:

- Livestock reduction – An effective measure in reducing manure and the associated methane emissions is a reduction in animal numbers. However, reduction of livestock will obviously have implications for farm profitability and for the size of the agricultural sector. This is not an acceptable solution as a stand-alone option; however, it may be possible to reduce methane emissions by combining improvements in animal efficiency with lower livestock numbers (O'Hara *et al.*, 2003).
- Prevention of anaerobic decomposition of manure during stabling of livestock – The way manure is stored and handled in stables determines the extent of methane production and emission. Higher temperature and longer storage periods favor growth of methanogenic bacteria. Storage of manure outside the stable may result in lower methane production because of lower out-door temperature in a moderate climate (de Jager *et al.*, 2001).
- Anaerobic digestion (covered lagoons) – In this process, manure solids are washed out of the livestock housing facilities with a large quantity of water and the resulting slurry flows into an anaerobic lagoon that has an impermeable cover. The recovered biogas can be used as an energy source and, occasionally, the liquid is withdrawn for use as fertilizer (de Jager *et al.*, 2001).
- Anaerobic digestion (on-farm mesophilic digestion) – Controlled anaerobic digestion can be operated in psychrophilic (10-20 ^{o}C), mesophilic (20-40 ^{o}C), or thermophilic (50-60 ^{o}C) range. Psychrophilic digestion requires long retention time and, thus, a large reactor. Therefore, psychrophilic digestion is only applicable when the reactor is also used for manure storage. On the other hand, mesophilic digestion requires less reactor volume, and it does not require heating for regions with warm climate (de Jager *et al.*, 2001).
- Anaerobic digestion (on-farm thermophilic digestion) – Thermophilic digestion requires even less retention time than mesophilic digestion and provides better pathogen reduction. However, it requires more complicated process control and additional energy for heating (de Jager *et al.*, 2001).
- Anaerobic digestion (centralized, off-farm mesophilic or thermophilic manure digestion) – Centralized storage and treatment of manure can have economic advantages than operating several farm-scale storage facilities at different locations. In addition, centralized storage/treatment of manure enables selection of an optimal location, for example, closer to end-users of energy such as local industry (de Jager *et al.*, 2001).

- Composting of animal manure – Composting reduces the amount of waste and turns it into a stable product that is more environmental friendly (little or no leachate production and gas emission) and may be used as soil amendments. The commonly-used composting techniques include windrow composting, minimal intervention (passive composting), and forced aeration (de Jager *et al.*, 2001).
- Aerobic digestion – The organics in manure can also be biodegraded under aerobic conditions. In this process, no methane will be generated and, thus, there will be little or no methane emissions.

Table 2.11 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from manure management. It should be noted that the data presented in this table are obtained from CEC (2005) and they are specific to California.

Table 2.11 – Technological Options for Manure Management Systems

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Covered lagoon, not including lagoon cost (large dairy)[1]	15	70	95	29	\$42.22	\$5.12	\$14.27
Covered lagoon, including lagoon cost (large dairy)[1]	15	30	95	29	\$56.30	\$5.12	\$14.27
2-stage plug flow digester (large dairy)[1]	15	1	95	100	\$96.38	\$5.12	\$14.27
Plug-flow digester[1]	15	34	95	100	\$69.27	\$5.12	\$14.27
Covered lagoon, not including lagoon cost (small dairy)[1]	15	70	95	29	\$145.67	\$5.12	\$14.27
Covered lagoon, including lagoon cost (small dairy)[1]	15	30	95	29	\$194.09	\$5.12	\$14.27
Centralized digester[1]	15	4	95	100	\$174.67	\$26.14	\$32.31

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: CEC (2005)

2.3.3 – Rice Cultivation

All rice in the United States is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in soil and floodwater and creates anaerobic conditions in soil. Under the anaerobic environment, methane is produced through decomposition of soil organic matter (mainly plant wastes that remain after harvest) by methanogenic bacteria. In California, there is typically one crop per year (Branosky & Greenhalgh, 2007). The methane produced goes through four different mechanisms: (1) the majority, 60 to 90%, is oxidized by aerobic methanotrophic bacteria in soil; (2) some becomes dissolved in floodwater; and (3) most of the remaining methane is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants; and (4) a minor amount of methane also escapes from soil through diffusion and bubbling through floodwater (USEPA, 2006a).

One of the most important factors affecting methane emissions is the water management system under which rice is grown. Under continuously flooded conditions, rice fields have higher methane emissions than those that are not flooded. Other factors that influence methane emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (USEPA, 2006a).

The methane emissions from rice cultivation in California were 0.6 $\mathrm{MMT_{CO2\text{-}Eq.}}$ in 2004, which is 2.2% of the state's total methane emissions, 27.8 $\mathrm{MMT_{CO2\text{-}Eq.}}$ (see Table 2.1).

Various mitigation strategies have been proposed; however, the formulation of such strategies is a very sensitive issue because the emission control measures may exert a negative impact on rice production (de Jager *et al.*, 2001). Specific technological options to reduce CH_4 emissions from rice cultivation include the following:

- Water management – Changes in the water management regime to reduce time over which anaerobic conditions in flooded field occur would reduce methane emissions (Graus *et al.*, 2004). Full midseason drainage may reduce methane emissions (USEPA, 2006b).
- Shallow flooding – In this option, rice paddies are marginally covered by flood water, with the water table fluctuating 5 to 10 cm above and below soil surface (USEPA, 2006b).
- Upland rice – Using upland rice, which can grow in dry land, can eliminate flood water in the field to reduce methane formation and emissions (USEPA, 2006b).
- Alter the amendments to soils – Adding amendments (e.g., phosphogypsum) to soils to inhibit methanogenesis would reduce methane emissions (Beach et al., 2006; Graus *et al.*, 2004).
- Use of alternative fertilizers – Using an alternative fertilizer (e.g., ammonium sulfate instead of urea) may also reduce methane emissions because sulfate additions to soil can elevate reduction potential, which suppresses methane production (USEPA 2006b; Beach *et al.*, 2006).
- Off-season straw – Shifting straw amendment from in-season to off-season (e.g., apply rice straw two months before rather than in the beginning of rice-growing season) can decrease availability of dissolved organic carbon and, thus, the population of methanogens (USEPA, 2006b).

2.3.4 – Field Burning of Agricultural Residues

Large quantities of agricultural crop residue are produced from farming activities. The crop types whose residues are typically burned in the United States are wheat, sugarcane, corn, barley, soybeans, peanuts, and rice. Less than 5% of these residues are burned each year, with the exception of a significantly higher proportion of rice straw residue burned. Crop residue burning is a net source of methane, which is released during combustion (USEPA, 2006a).

The methane emissions from field burning of agricultural residues in California were 0.1 $\mathrm{MMT_{CO2\text{-}Eq.}}$ in 2004, which is 0.4% of the state's total methane emissions, 27.8 $\mathrm{MMT_{CO2\text{-}Eq.}}$ (see Table 2.1). It should be noted here that there is some controversy regarding emissions reported under "other waste burning" in the inventory reports, but, generally, the numbers used in the CARB's inventory reflects the preferred methodology at this time (Church, 2007).

The mitigation options for reducing methane emissions from field burning of agricultural residue include improved fire management practices, plowing under, or composting (Gale & Freund, 2002).

2.4 – Land-use Change and Forestry

The only potential source for methane emissions in this sector is forest fires. Methane emissions from this sector are not included in the most recent inventory report by CEC (CEC, 2006). No practical technological options for reducing methane emissions in this sector were found in the literature search.

2.5 – Wastes

2.5.1 – Landfills

Landfills are the largest anthropogenic source of methane emissions in the United States, 140.9 $MMT_{CO2\text{-}Eq.}$ in 2004, or 25.3% of total methane emissions. Municipal solid waste (MSW) landfills accounted for 94% of the total landfill emissions, while industrial landfills accounted for the reminder, 6%. Landfills are also the largest anthropogenic source of methane emissions in California, 8.4 $MMT_{CO2\text{-}Eq.}$ in 2004, or 30.2% of the state's total methane emissions, 27.8 $MMT_{CO2\text{-}Eq.}$ (see Table 2.1).

After being placed in a landfill, the organic portion of the waste is initially decomposed aerobically. The environment will turn anaerobic after the available oxygen is consumed. The remaining organic matter is available for consumption by anaerobic bacteria. Some of this matter is converted into landfill gas with a typical composition of approximately 50% carbon dioxide and 50% methane by volume. It should be noted that methane concentration is time-dependent and it decreases over time. Significant methane production typically starts one or two years after waste is buried and continues for 10 to 60 years (USEPA, 2006a).

Factors affecting methane emissions from landfills include (1) the amount of waste buried, (2) waste characteristics (composition, size, moisture content), (3) ambient conditions (temperature, air infiltration rate, and water infiltration rate), (4) amount of landfill gas extraction for flaring or energy recovery, and (5) amount of methane oxidized in landfills instead of being released to the atmosphere.

Although the annual quantity of waste buried in landfills in the United States increased 33% from 1990 to 2004, net annual methane emissions decreased by approximately 18%. The downward trend in overall methane emissions from landfills is due to the increasing amount of landfill gas collected and combusted by landfill operators (USEPA, 2006a). State of California started collecting and combusting landfill gas earlier than other states. Thus, the trend in California is that methane emissions from landfills are relatively flat from 1990 onward, since the controls were largely in place before 1990 (Church, 2007). US EPA has the voluntary Landfill Methane Outreach Program underway as part of the Climate Change Action Plan toward emission reductions (de la Chesnaye *et al.*, 2001).

Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006). Specific technological options to reduce CH_4 emissions from landfills include the following:

- Landfill gas recovery and utilization (direct gas use) – Landfill gas is recovered and used as a medium BTU fuel for boilers or industrial processes. The gas is directly piped to a near-by user and serves as a replacement fuel.
- Landfill gas recovery and utilization (electricity generation) – Recovered landfill gas is used for electricity generation projects.

- Landfill gas recovery and utilization (upgrade to natural gas) – Several methods such as membrane separation can separate carbon oxide and other compounds in landfill gas from methane. The treated gas can be injected to a local natural gas distribution grid. The recovered gas can also be converted to compressed natural gas (CNG), liquefied natural gas (LNG), methanol, or ethanol (US Climate Change, 2005).
- Anaerobic digestion – Using a reactor vessel to enhance natural decomposition under anaerobic environment. The temperature, moisture content, and pH are maintained close to their optimal values. The generated methane can be used to produce heat and/or electricity (USEPA, 2004).
- Anaerobic digestion (includes additional cost for waste separation) – Similar to the above-mentioned option, anaerobic digestion, but this option includes the cost of source separation of waste prior to disposal in the anaerobic digestion system (IEA, 2003).
- Composting – This option involves degradation of organic matter under aerobic conditions. It requires separating organic matter from the waste stream. Finished compost has a market value, used to enhance soil in horticulture/landscape and agricultural sites (USEPA, 2004; IEA, 2003).
- Mechanical biological treatment – In this option, the whole waste stream is composted in order to degrade the organic fraction anaerobically. The inorganic fraction needs to be disposed of in a landfill (USEPA 2003; IEA, 2003).
- Increased oxidation – Methane emissions are reduced by the top capping and restoration layers of the landfills. A clay cap minimizes methane leakage, while the landfill soil cover above the clay cap oxidizes the escaping methane (USEPA, 2004; Inamori *et al.*, 2003).
- Optimize and enhance landfill gas formation – Moisture is pivotal for biological activities. An increase of moisture content and enhancement of moisture movement accelerate the speed and increase the completeness of conversion of organics to landfill gas. Consequently, control of moisture (e.g., by infiltrating water or leachate) enables control over landfill gas production and probably emissions (de Jager *et al.*, 2001).
- Waste treatment in bioreactors (the sustainable landfill) – An alternative to traditional sanitary landfill is waste treatment in a bioreactor in which biological, chemical, and physical processes occur in a controlled way. In this approach waste is deposited in relatively small and shallow compartments with an impermeable bottom liner. The waste filling period is kept short, one year at maximum, to prevent the on-set of methanogenesis before the top liner is installed. After the installation of the top liner, biological process in the waste is accelerated through infiltration and recirculation of leachate (Delhotal *et al.*, 2006; de Jager *et al.*, 2001). They are currently two bioreactor processes - anaerobic and aerobic. Hybrid bioreactors employ both methods (US Climate Change, 2005)
- Aerobic landfilling or aerobic pretreatment – Maintaining aerobic conditions in the landfill or the aerobic pretreatment is a way for reducing methane emissions. One option to maintain aerobic conditions is to inject compressed air, 3 to 7 bar, into the landfill and position several extraction wells in strategic locations to collect the product gas mixture. If aerobic pretreatment is practiced, the biodegradable organics are converted to carbon dioxide and the waste will have less or negligible methane formation potential after landfilling (de Jager *et al.*, 2001).
- Source reduction – Methane is the end-product of waste degradation in landfills. Reducing the amount of degradable waste landfilled will reduce methane emissions. It can be achieved

from practices such as waste prevention, recycling, composting, fermentation, or waste incineration (de Jager & Blok, 1996).

Table 2.12 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from manure management. It should be noted that the data presented in this table for the options of direct gas use and electricity generation are obtained from CEC (2005) and they are specific to California.

2.5.2 – Wastewater Treatment

Wastewater from domestic and industrial sources is treated to remove suspended solids, organics, pathogens, and some chemical constituents. Removal of organics is typically done by aerobic or anaerobic biological processes in which microorganisms decompose the organics for cell maintenance and growth. The resulting biosolids (sludge) are removed from the liquid effluent prior to discharge to receiving waters. The biosolids may be further biodegraded aerobically or anaerobically. During collection and treatment, wastewater and sludge may be accidentally or deliberately managed under anaerobic conditions. Under these conditions, methane would be formed as a by-product.

In the United States, methane emissions from domestic wastewater treatment in 2004 were 20.0 $MMT_{CO2\text{-}Eq.}$ The emission rates are increasing due to the increase in the U.S. human population and the increase in per capita organic loading to wastewater.

In the United States, methane emissions from industrial wastewater treatment in 2004 were 16.9 $MMT_{CO2\text{-}Eq.}$ The industrial emission sources are those generate wastewater with high biodegradable organic concentrations; they include (USEPA, 2006a):

- Pulp and paper
- Meat and poultry packing
- Vegetables, fruits and juice processing
- Refineries
- Petrochemicals
- Starch production (insignificant emissions)
- Alcohol refining (insignificant emissions)
- Creameries (insignificant emissions)
- Textile (insignificant emissions)

The methane emissions from wastewater treatment in California were 1.7 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 6.1% of the state's total methane emissions, 27.8 $MMT_{CO2\text{-}Eq.}$ (see Table 2.1).

Table 2.12 – Technological Options for Landfill

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Direct gas use (WIP[3] <100,001 tons)[1]	15	0	85	14	\$152.91	\$4.97	\$9.25
Direct gas use (WIP 100,001 – 200,000 tons)[1]	15	0	85	4	\$68.57	\$3.70	\$9.18
Direct gas use (WIP 200,001 – 300,000 tons)[1]	15	0	85	4	\$47.44	\$3.41	\$9.07
Direct gas use (WIP 300,001 – 400,000 tons)[1]	15	33	85	4	\$41.74	\$3.51	\$9.36
Direct gas use (WIP 400,001 – 500,000 tons)[1]	15	50	85	8	\$37.73	\$3.63	\$9.34
Direct gas use (WIP 500,001 – 1,000,000 tons)[1]	15	29	85	23	\$23.09	\$3.29	\$9.34
Direct gas use (WIP 1,000,000+ tons)[1]	15	31	85	43	\$15.00	\$3.13	\$9.16
Electricity (WIP <100,001 tons)[1]	15	100	85	14	\$169.53	\$6.59	\$7.81
Electricity (WIP 100,001 – 200,000 tons)[1]	20	100	85	4	\$88.04	\$5.31	\$7.76
Electricity (WIP 200,001 – 300,000 tons)[1]	20	100	85	4	\$67.39	\$5.00	\$7.67
Electricity (WIP 300,001 – 400,000 tons)[1]	20	67	85	4	\$62.57	\$5.15	\$7.91
Electricity (WIP 400,001 – 500,000 tons)[1]	20	50	85	8	\$58.70	\$5.27	\$7.89
Electricity (WIP 500,001 – 1,000,000 tons)[1]	20	71	85	23	\$44.54	\$4.94	\$7.90
Electricity (WIP 1,000,000+ tons)[1]	20	69	85	43	\$36.27	\$4.74	\$7.74
Anaerobic digestion[2]	15	-	95	100	\$400.98	\$67.61	\$8.74
Anaerobic digestion (with additional cost for waste separation)[2]	15	-	95	100	\$484.91	\$125.89	\$5.25
Composting[2]	15	-	100	100	\$359 - \$424	\$81.59 - \$93.25	\$0.00
Mechanical biological treatment[2]	15	-	95	100	\$359.02	\$121.23	\$0.00
Increased oxidation[2]	50	-	44	100	\$465.43	\$0.63	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{\text{CO2-Eq.}}$
1: CEC (2005); 2: IEA (2003) & USEPA (2004); 3: WIP = waste-in-place

Key reduction options for methane emissions from wastewater are addition of more wastewater treatment plants, aerobic wastewater treatment, and recovery of methane from anaerobic wastewater treatment processes (Lucas *et al.*, 2006). Specific technological options to reduce CH_4 emissions from wastewater include the:

- Aerobic wastewater treatment – Aerobic wastewater treatment processes such as activated sludge systems, oxidation ditch, trickling filters, waste stabilization ponds, and others can biodegrade organics and reduce the methane emission potential.
- Upgrading of existing overloaded or under-aerated wastewater treatment plants – Implementation of this option will greatly reduce the methane emission potentials from those plants (de Jager *et al.*, 2001).
- Anaerobic treatment – Anaerobic treatment can also be applied to wastewater, especially that of high organic concentrations. The methane gas produced will be collected and then destructed or used for electricity generation (USEPA, 2006b).

References

Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.

Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) "Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions", *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.

Branosky, E.; Greenhalgh, S. (2007) "Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.

California Air Resources Board (2004) "Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles", California Air Resources Board, August 6, 2004.

California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.

Church, S. (2007) Personal communication – reviewers' comments on the Task 1 Report of this project on February 20, 2007, California Air Resources Board.

Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.

Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) "Global Estimates of Potential Mitigation of Greenhouse Gas Emissions by Agriculture", *Nutrient Cycle in Agroecosystems*, 52, 221-228.

de Jager, D.; Blok, K. (1996) "Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands", *Energy Convers. Mgmt.* 37(6-8), 1181-1186.

de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.

de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) “Methane and Nitrous Oxide Mitigation in Agriculture’, *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 89-108.

Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.

Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology,* June.

Graus, W., Harmelink , M. and Hendriks, C. (2004) “Marginal GHG-Abatement Curves for Agriculture”, Ecofys, Utrecht, the Netherlands.

Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.

Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.

Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.

International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

Intergovernmental Panel on Climate Change - IPCC (1997), “Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories”, United Nations Intergovernmental Panel on Clime Change.

Intergovernmental Panel on Climate Change - IPCC (2000), “Climate Change 2000 - The Third Assessment Report”, Working Group 3, Final Draft, October 2000.

Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change” - The Third Assessment Report - Working Group I, January, 2001.

Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.

O'Hara, P.; Freney, J.; Ulyatt (2003) "Abatement of Agricultural Non-carbon Dioxide Greenhouse Gas Emissions – A Study of Research Requirements", a report prepared for the Ministry of Agriculture and Forestry, New Zealand.

Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.

U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.

U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).

U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.

U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

CHAPTER 3

NITROUS OXIDE

3.0 – Introduction

Nitrous oxide (N_2O) is produced from natural and anthropogenic sources. Under ambient conditions, it is a colorless inflammable gas, with a pleasant, slightly sweet odor and taste (Wikipedia, 2007). It is chemically stable and has little impact on human health and other living organisms at its normal atmospheric concentration (Moritomi and Mochida, 2000). However, it is a significant greenhouse gas with approximately 296 times the global warming potential of CO_2 over a 100-year time horizon (IPCC, 2001). The nitrous oxide concentration in the atmosphere has increased by about 18% over the last two hundred years, from 275 parts per billion by volume (ppbV) in pre-industrial times to 311 ppbV in 1992 (IEA, 2000). This increase was mainly due to anthropogenic emissions, including agricultural soil management, manure management, production of nitric acid and adipic acid, wastewater, and stationary and mobile combustions (USEPA, 2006a).

Table 3.1 summarizes the N_2O emissions from various sectors in California and in the United States. The data were extracted from the recent inventory reports of USEPA and CEC (USEPA, 2006a; CEC 2006).

Table 3.1 – Summary of Nitrous Oxide Emissions in the USA and California

	USA (2004)		**California (2004)**		
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Agricultural Soil Management	261.5	67.5%	19.16	57.5%	7.3%
Mobile Combustion	42.8	11.0%	11.78	35.3%	27.5%
Manure Management	17.7	4.6%	0.89	2.7%	5.0%
Nitric Acid Production	16.6	4.3%	0.15	0.5%	0.9%
Human Sewage	16.0	4.1%	1.07	3.2%	6.7%
Stationary Combustion	13.7	3.5%	0.19	0.6%	1.4%
Settlements Remaining Settlements	6.4	1.7%	-	-	-
Adipic Acid Production	5.7	1.5%	-	-	-
Nitrous Oxide Usage	4.8	1.2%	-	-	-
Municipal Solid Waste Combustion	0.5	0.1%	0.02	0.1%	4.0%
Field Burning of Agricultural Residues	0.5	0.1%	0.07	0.2%	14.0%
Forest Land Remaining Forest Land	0.4	0.1%	-	-	-
International Bunker Fuels	0.9	0.2%	-	-	-
Total	**387.5**	100%	**33.33**	100%	**8.6%**

As shown in Table 3.1, N_2O emissions in California account for approximately 8.6% of the nationwide N_2O emissions. The top five contributors for N_2O emissions in the United States are agricultural soil management (67.5%), mobile combustion (11.0%), manure management (4.6%), nitric acid production (4.3%), and human sewage (4.1%). The contributors for N_2O emissions in California, in the order of magnitude, are agricultural soil management (57.5%), mobile combustion (35.3%), human sewage (3.2%), manure management (2.7%), stationary combustion (0.6%), nitric acid production (0.5%), field burning of agricultural residues (0.2%), and municipal solid waste combustion (0.1%). N_2O emissions in California occur from all six major sectors: energy, industrial processes, solvent use, agricultural, land-use change and forestry, and waste. The percentage emissions of major sources in the USA and California are also plotted, in a descending order, in Figures 3.1 and 3.2, respectively.

Figure 3.1 – Major Sources of Nitrous Oxide Emissions in the USA

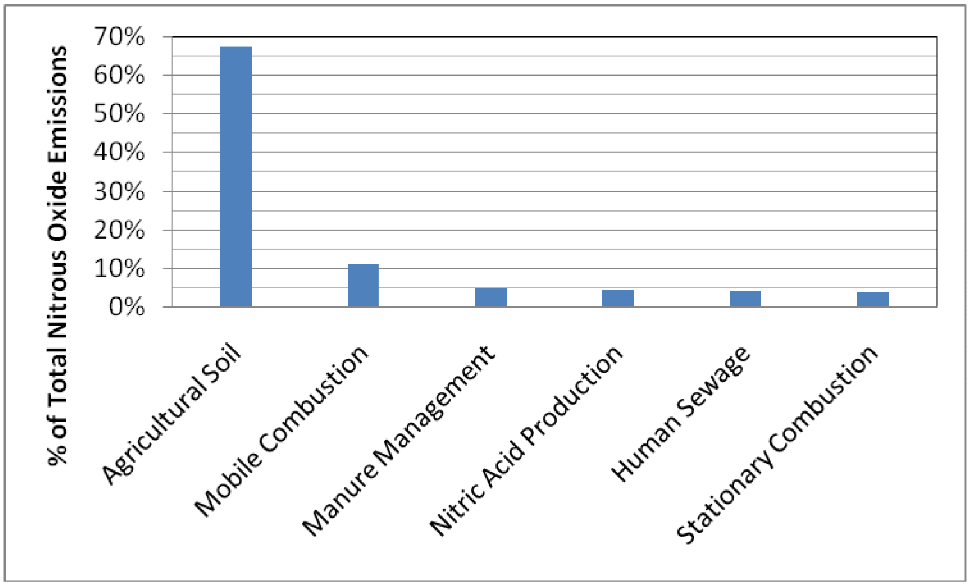
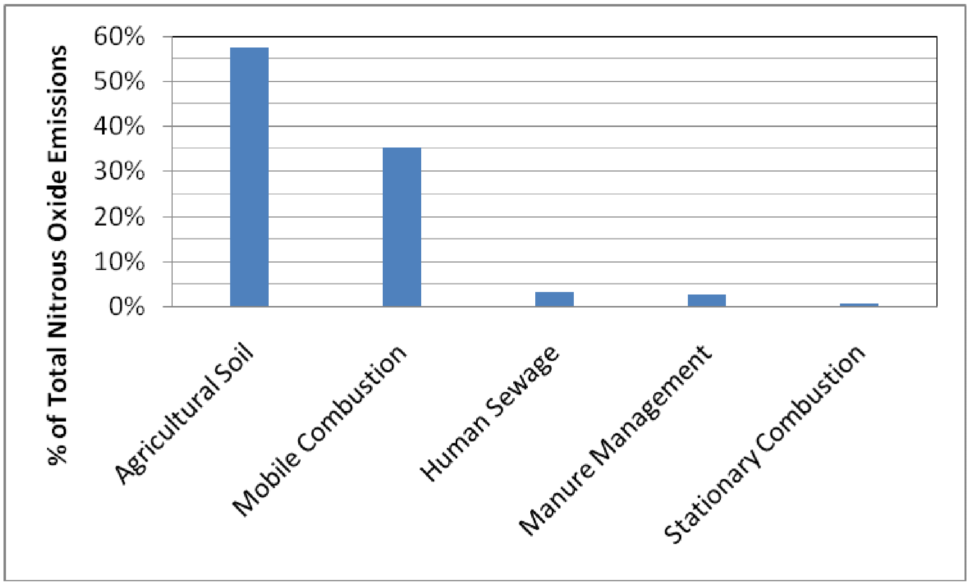


Figure 3.2 – Major Sources of Nitrous Oxide Emissions in California



3.1 – Agriculture

The agricultural sector is currently and will remain the dominant source of nitrous oxide emissions in both California and the United States in the foreseeable future (USEPA, 2003). The N_2O emissions from the activities related to agriculture were 279.7 $MMT_{CO2\text{-}Eq.}$ in the United States in 2004. Agricultural soil management accounts for 67.5% of all N_2O emissions in the United States; while manure management is the third largest at 4.6% (see Table 3.1). Field burning of agricultural residues is a minor source, at 0.1%. N_2O emissions from agricultural activities in California were 20.12 $MMT_{CO2\text{-}Eq.}$ in 2004, 7.2% of the nationwide N_2O emissions from agriculture. Similar to its dominance as the N_2O source in the United States, agricultural soil management accounts for >95% of California's N_2O emissions from agricultural activities in 2004 (see Table 3.2).

Table 3.2 – N_2O Emissions from Agriculture Sources in the USA and California

	USA (2004)		**California (2004)**		
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Agricultural Soil Management	261.5	93.5%	19.16	95.2%	7.3%
Manure Management	17.7	6.3%	0.89	4.4%	5.0%
Field Burning of Agricultural Residues	0.5	0.2%	0.07	0.3%	14.0%
Total	**279.7**	100%	**20.12**	100%	**7.2%**

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification (the aerobic microbial oxidation of ammonium to nitrate) and denitrification (the anaerobic reduction of nitrate to nitrogen and/or nitrous oxide). N_2O is one of the intermediate products in both the nitrification and denitrification processes.

3.1.1 – Agricultural Soil Management

Several agricultural activities increase mineral nitrogen availability in soils for nitrification and denitrification and ultimately increase the amount of N_2O emissions. These activities increase soil nitrogen availability directly or indirectly. Activities that will directly increase the nitrogen availability include (USEPA, 2006a):

- Fertilization
- Application of managed livestock manure or other organics such as wastewater sludge
- Deposition of manure by domestic animals in pastures, rangelands, and paddocks
- Production of nitrogen-fixing crops and forages
- Retention of crop residues
- Cultivation of organic soils
- Others including irrigation, drainage, tillage practices, and fallowing of land

Indirect emissions can occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied nitrogen, and (2) surface runoff and leaching of applied nitrogen into surface water and groundwater. Emissions from surface runoff and leaching were reported as a separate group in the most recent California GHG inventory report by CEC (2006), as shown in Table 3.3.

Annual N_2O emissions from agricultural soils in the United States fluctuated between 1990 and 2004; the emissions in 2004 were 261.5 $\text{MMT}_{\text{CO2-Eq.}}$ in 2004, 1.7% lower than those in 1990. The fluctuations are largely due to annual variation in weather patterns, synthetic fertilizer use, and crop production (USEPA, 2006a).

Table 3.3 – N_2O Emissions from Agricultural Soil Management in the USA and California

	USA (2004)		**California (2004)**		
Activity	**$\text{MMT}_{\text{CO2-Eq.}}$**	**(%)**	**$\text{MMT}_{\text{CO2-Eq.}}$**	**(%)**	**CA/USA**
Direct	170.9	65.4%	7.10	37.0%	4.2%
Cropland	133.8				
Grassland	37.2				
Indirect	90.6	34.6%	8.09	42.2%	8.9%
Leaching/Runoff	-	-	3.98	20.8%	-
Total	**261.5**	**100.0%**	**19.2**	**100.0%**	**7.3%**

The N_2O emissions from agricultural soil management in California were 19.2 $\text{MMT}_{\text{CO2-Eq.}}$ in 2004, 57.5% of the state's total N_2O emissions, 33.3 $\text{MMT}_{\text{CO2-Eq.}}$ (see Table 3.2)

Although most of the N_2O emissions from agricultural activities are from soils, the emission flux of N_2O per unit surface area of soil is small and varies greatly across time and space. The flux rate depends significantly on soil type, climate conditions, and soil management practices (IEA, 2000). Basically, there are two types of strategies and related technological options that are applicable to emission reduction of N_2O from agricultural soils. The first type uses measures that improve efficiencies in nitrogen utilization, and the second type inhibits the formation of nitrous oxide (Kowalenko, 1999). It should be noted that there are overlaps in these two types. For example, the use of the nitrification inhibitor and change in irrigation practices are also measures for improving nitrogen fertilizer efficiencies in the field.

With regards to improving nitrogen utilization efficiencies to reduce N_2O emission from agricultural soil, many technological options and practices have been mentioned in literature. However, many of them were mentioned without detailed discussion and information. In addition, very few studies include cost data for implementing mitigation options (DeAngelo *et al.*, 2006). The economic potential for nitrous oxide emission reduction probably is low, except perhaps for efficient fertilizer use (Blok and de Jager, 1994). Below are a list and a brief description of the technological options and practices found from the literature search (Detailed information for some of these options can be found in Appendix B):

- Soil testing to optimize nitrogen application rate – More nitrogen is usually applied to soil than is needed because of the concern of production lost by under-fertilizing (Branosky & Greenhalgh, 2007). Soil nitrogen testing can be used to help growers adjust nitrogen application rates to match site-specific conditions and have more efficient use of fertilizers (IEA, 2000; O'Hara *et al.*, 2003). The abatement cost for the soil testing option is approximately \$5/$\text{MT}_{\text{CO2-Eq.}}$ (Gale and Freund, 2002).
- Controlled released fertilizers (CRFs) – The CRFs are intended to release nutrients at a rate that corresponds with nutrient demand of growing crops. Typically, there is a physical barrier (e.g., a polymer coating) that decreases the rate of nutrient release into the soil. The

coatings can be adjusted to match the release rate to the requirements of specific plants (Dalal *et al.*, 2003; IEA, 2000). However, as the release of nutrients from CRFs depends on several factors (temperature, water, root structure), this may be difficult to achieve in practice (Bates, 2001). The abatement cost for the CRF option is approximately \$50/MT$_{\text{CO2-Eq.}}$ (Gale and Freund, 2002).

- Changes in the timing and/or frequency of fertilizer application – The use of fertilizer will be more efficient when the fertilizer application coincides with the period of rapid plant uptake. Several applications of small amounts (split applications) during the growing season would be a more effective means of supply nitrogen for plan growth and the N_2O emission loss should be smaller (IEA, 2000). However, it may not always be practical (Bates, 2001).

- Matching fertilizer nitrogen type to season and general weather pattern – Nitrate-based fertilizer is less stable in soil than the ammonia-based fertilizer. When leaching potential is high, ammonia-based fertilizer should be used. An example is to use ammonium-based fertilizer when it is wet and nitrate-based fertilizer when it is dry (McTaggert *et al.*, 1994).

- Crop rotation options – Crop rotation entails the growing of different annual or perennial crops in a given field. It is often used as a strategy for improving soil conditions as well as a component of pest control. Corn-alfalfa rotations might also be an effective means of reducing the use of synthetic fertilizers (IEA, 2000).

- Substitute manure for chemical fertilizer – If commercial fertilizers are replaced with livestock manure, N_2O emission from chemical fertilizers can be reduced without increasing emissions from manure (IEA, 2000; de la Chesnaye *et al.*, 2001). Early application and immediate incorporation of manure into soil would reduce the direct N_2O emissions and ammonia volatilization (Dalal *et al.*, 2003).

- Tailor fertilizer to local conditions – It might be possible to develop fertilizer types that are more suitable to specific local conditions and/or adjust application rates to take into account of soil characteristics, soil moisture content, and ambient and soil temperature (IEA, 2000).

- Cover crops – Winter or fallow cover crops can prevent the build-up of residual soil nitrogen, catching nitrogen that would otherwise be emitted as N_2O or leached (Cole *et al.*, 1997; Kroeze & Mosier, 2000; Bates, 2001).

- Improvement of fertilizer spreading – With better spreader maintenance, more uniform spreading can be achieved to increase efficiency and avoid over-application or under application (Worrell, 1994; DeAngelo *et al.*, 2006). Maintaining a fertilizer zone on the edge of fields to prevent losses into ditches at the side of fields would reduce fertilizer loss. Optimization of fertilizer distribution geometry can also prevent losses into ditches (Worrell, 1994). Fertilizer banding can increase efficiency of nitrogen use, reduce volatilization up to 35%, and increase yield up to 15% (Cole *et al.*, 1997; Kroeze and Mosier, 2000). In the band-mode application of easily soluble fertilizer, which was locally put into depth of 10 cm below vegetation, the N_2O emission rate was greatly reduced in comparison with that in broadcasting application (Tsuruta & Aliyama, 2000). Use of precision farming technologies such as yield mapping, global positioning system, and automatic sensing allows crop performance and output to be measured in different areas of a specific field and has potential in reducing nitrogen application and the N_2O emissions (Bates, 2001). Avoiding nitrogen fertilization on urine spots, through precision fertilization, reduced N_2O emissions (Kasper *et al.*, 2002).

- Simple fertilization reduction – This option is to reduce nitrogen-based fertilizer from one-time baseline application of 10%, 20%, or 30% (USEPA, 2006b). However, using this option will have a risk of under-fertilization (DeAngelo *et al.*, 2006).

- Maintain plant residue on the production site – It will allow the nitrogen contained in the residue to be reused, thus reducing the requirement of synthetic fertilizer. It should directly reduce the N_2O production from fertilizer and eliminate the N_2O emission from burning of the plant residue (IEA, 2000).

With regards to inhibition of N_2O formation to reduce its emission from agricultural soil, there are many technological options and practices mentioned in the literature; but most of them were mentioned without detailed discussion and information. Below are a list and a brief description of the technological options and practices found from the literature search (Detailed information for some of these options can be found in Appendix B):

- Nitrification inhibitors – Nitrogen applied must be nitrified to nitrate before it is available for denitrification. Nitrification inhibitors delay the transformation of ammonium to nitrate (Cole *et al.*, 1997; Kroeze and Mosier, 2000). They can reduce the loss of nitrogen and permit crop production at constant or improved yields at given fertilizer application rates. The abatement cost for the nitrification inhibitor option is approximately \$70/$MT_{CO2\text{-}Eq.}$ (Gale and Freund, 2002).
- Urease inhibitors – Urease inhibitors delay the transformation of urea to ammonium to help matching the timing of nitrogen supply with crop demand (Cole *et al.*, 1997; Kroeze and Mosier, 2000).
- Alternative tillage systems – Some studies suggested that N_2O emissions could decline as a result of reduced nitrogen application rates following a shift to no till agriculture (Lemke *et al.*, 1999). Conversion from conventional tillage to no till will cause less disturbance to soils and more crop residual is retained (USEPA, 2006b)
- Changes in irrigation practices – Because soil-water content is an important factor in volatilization as well as nitrification/denitrification, irrigation practices can have an important impact on N_2O emissions from agriculture (Lemke *et al.*, 1999). However, the appropriate use of irrigation water is site-, crop-, soil-, and temperature-specific, therefore this option may not be easy for practical application.
- Improving drainage and avoiding soil compaction – Improving drainage and preventing soil compaction can reduce N_2O emission by 3% (Branosky & Greenhalgh, 2007; O’Hara *et al.*, 2003).

3.1.2. – Manure Management

Livestock manure can produce N_2O emissions, as part of the nitrogen cycle through nitrification and denitrification of organic nitrogen compounds in manure and urine. The extent of N_2O production depends on the composition of the manure and urine, types of bacteria involved in the process, moisture, and oxygen content in the manure management system. As mentioned, N_2O is one of the intermediate products in the nitrification and denitrification process. The N_2O emissions are most likely to occur in dry manure handling systems that have aerobic conditions for nitrification, but also contain pockets of anaerobic conditions, due to water saturation, for denitrification (USEPA, 2006a).

The N_2O emissions in the United States from manure management were 17.7 $MMT_{CO2\text{-}Eq.}$ in 2004; a 9% increase from 1990. The emission rates depend heavily on the population of the livestock and types of manure management systems (liquid vs. dry). Poultry (7.4 $MMT_{CO2\text{-}Eq.}$), beef cattle (5.7 $MMT_{CO2\text{-}Eq.}$), and dairy cattle (3.8 $MMT_{CO2\text{-}Eq.}$) accounted for more than 90% of the total, 17.7 $MMT_{CO2\text{-}Eq.}$, while swine, horses, sheep, and goat made the balance (USEPA, 2006a).

The N_2O emissions from manure management in California were 0.89 $MMT_{CO2\text{-}Eq.}$ in 2004, 2.7% of the state's total nitrous oxide emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (see Table 3.1).

With regards to reducing N_2O emission from manure management systems, there are several technological options and practices mentioned in the literature. Below are a list and a brief description of the technological options and practices found from the literature search:

- Optimizing the crude protein/energy ratio in animal diets – Some exploratory work has been performed on altering quantity of nitrogen excreted by domestic livestock by changing feed in such a way as to reducing nitrogen intake (Bates, 2001; IEA, 2000). One approach is to feed high quality diets which are low in protein. In one experiment it was found that the reduction in urinary nitrogen was 24% (O'Hara *et al.*, 2003). An attractive forage for cattle in this respect is corn silage, which reduces nitrogen intake, but improves utilization of the ingested nitrogen (de Jager *et al.*, 2001). Dairy cows fed with grasses high in water-soluble carbohydrate excreted 24% less nitrogen than those with normal diets (O'Hara *et al.*, 2003). Reduction of nitrogen output by pigs can be achieved by matching dietary protein concentration to physiological requirement. Other options include reduction of protein content, improvement of amino acid profile by amino acid supplementation, breeding and gene technology, and the use of feed additives (de Jager *et al.*, 2001).
- Nitrification and urease inhibitors – Nitrification and urease inhibitors can be used to reduce N_2O emissions from livestock manure. This option appears to be rather expensive (IEA, 2000).
- Waste storage – A shift towards anaerobic storage rather than aerobic storage of manures may reduce N_2O losses by a factor of 10 (Cole *et al.*, 1997; Kroeze and Mosier, 2000). However, it may also increase methane emission by a factor of 10, unless measures to capture and destroy methane are implemented (Bates, 2001).
- Use of cattle feed-pads during winter months – By keeping cattle on feed-pads during autumn/winter period, excretes can be collected and utilized as fertilizer later (Branosky & Greenhalgh, 2007; O'Hara *et al.*, 2003).
- Reducing the number of animals by increasing their productivity (Lucas *et al.*, 2006)
- Optimizing manure management and limiting grazing (Lucas *et al.*, 2006)

3.1.3 – Field Burning of Agricultural Residues

Large quantities of agricultural crop residues are produced from farming activities. The crop types whose residues are typically burned in the United States are wheat, sugarcane, corn, barley, soybeans, peanuts, and rice. Less than 5% of these residues are burned each year, with the exception of a significantly higher percentage for rice straw. Crop residue burning is a net source of nitrous oxide, which is released during combustion (USEPA, 2006a).

In the United States, nitrous oxide emissions from field burning of agricultural residues in 2004 were 0.4 $MMT_{CO2\text{-}Eq.}$ The nitrous oxide emissions from these activities in California were 0.07 $MMT_{CO2\text{-}Eq.}$ in 2004, a very small fraction of the state's total nitrous oxide emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (see Table 3.1). It should be noted here that there is some controversy regarding emissions reported under "other waste burning" in the inventory reports, but, generally, the numbers used in the CARB's inventory reflects the preferred methodology at this time (Church, 2007).

The mitigation options for reducing N_2O emissions from agricultural residue include improved fire management practices, plowing under, or composting (Gale & Freund, 2002).

3.2 – Energy

Table 3.4 summarizes the N_2O emissions from the energy sector in California and in the United States. As shown, N_2O emissions from mobile combustion in California account for 27.5% of the nationwide emissions in this sector, which seems to be unreasonably high. It may be due to the differences in how the emissions from this source were estimated and reported by two inventory reports. Mobile combustion is the dominant contributor to N_2O emissions in the energy sector in California, at 98.2% (see Table 3.4).

Table 3.4 – Summary of N_2O Emissions from Energy Sector in the USA and California

	USA (2004)		**California (2004)**		
Source	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Mobile Combustion	42.8	75.1%	11.78	98.2%	27.5%
Stationary Combustion	13.7	24.0%	0.19	1.6%	1.4%
Municipal Solid Waste Combustion	0.5	0.9%	0.02	0.2%	4.0%
Total	**57**	100 %	**11.99**	100%	**21.0%**

3.2.1 – Mobile combustion

In the mobile combustion sector, N_2O is emitted as a by-product of fuel combustion. N_2O emissions from mobile sources depend on characteristics of fuel, air-fuel ratios, combustion temperatures, maintenance and operation practices, and usage of pollution control equipment (USEPA, 2006a).

Emissions from mobile combustion are often grouped by transport mode (e.g., highway, air, rail), fuel type (e.g., motor gasoline, diesel fuel, jet fuel), and vehicle type (e.g., passenger cars, light-duty trucks). Road transport accounted for the majority of mobile source fuel consumption, and, hence, the majority of mobile combustion emissions (Table 3.5).

Mobile combustion is the second largest source of N_2O in the United States, at 11% or 42.8 $MMT_{CO2\text{-}Eq.}$ in 2004 (see Table 3.1). N_2O emissions from vehicles have only recently been studied in detail and they mainly come from the catalytic converters. Present converters, using so-called three-way catalysts, are only designed to reduce emissions of ozone precursors such as volatile organic compounds (VOCs), CO, and nitrogen oxides (NO_x), thereby increasing N_2O emissions with respect to uncontrolled emissions (Lucas *et al.*, 2006). Use of these catalytic converters resulted in an increase of N_2O emission in the United States between 1990 and 1998. However, N_2O emissions have subsequently declined from mobile sources as improvements in emission control technologies employed on new vehicles. As a result, N_2O emissions from mobile sources in 2004 were 1% lower than that in 1990 in the United States (USEPA, 2006a). As shown in Table 3.1, the N_2O emissions from mobile combustion in California were 11.8 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 35.3% of the state's total N_2O emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ There is a discrepancy between the reported estimates on emissions for diesel highway; the reported emission value for the United States by USEPA (0.3 $MMT_{CO2\text{-}Eq.}$) is much smaller than that for California by CEC (8.13 $MMT_{CO2\text{-}Eq.}$), as shown in Table 3.5. The discrepancy may be due to the differences how the emissions from this source were estimated and reported by two inventory reports (Church, 2007). It should be noted here that the ARB's new inventory (http://www.arb.ca.gov/cc/inventory/data/data.htm - last updated on November 19, 2007) reported N_2O emission from the on-road all diesel vehicles to be 0.023 $MMT_{CO2\text{-}Eq.}$ in California, which is more consistent with the national inventory.

Table 3.5 – N_2O Emissions from Mobile Sources in California and the USA

	USA (2004)		California (2004)		
Activity	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**$MMT_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Gasoline Highway	**38.6**	**90.2%**	**3.65**	**31.0%**	**9.5%**
Passenger Cars	21.0				
Light-Duty Trucks	16.7				
Heavy-Duty Vehicles	0.9				
Motorcycles	<0.05				
Diesel Highway	**0.3**	**0.7%**	**8.13**	**69.0%**	**2710.0%**
Passenger Cars	<0.05				
Light-Duty Trucks	<0.05				
Heavy-Duty Vehicles	0.3				
Alternative Fuel Highway	**0.1**	**0.2%**			
Non-Highway	**3.7**	**8.6%**			
Ships and Boats	0.4				
Locomotives	0.4				
Farm Equipment	1.8				
Construction Equipment	0.4				
Aircraft	0.5				
Other	0.4				
Total	**42.8**	**100%**	**11.78**	**100%**	**27.5%**

The degree to which N_2O emissions have increased (or decreased) from mobile sources depends upon factors such as driving practices (i.e., number of cold starts) and size, type, and age of the catalyst. The production of N_2O emissions can increase up to a factor of 10 to 16 due to aging of the catalyst (de Jager *et al.*, 2001). N_2O emissions from mobile sources for areas with a high number of road vehicles with emission controls, therefore, can be substantial (USEPA, 2006a). The technological options for reducing N_2O emission from mobile sources include the following:

- Improve catalyst performance – In most of the existing catalytic converters, N_2O is produced as a result of an incomplete reduction of NO_x to NO. In the longer term it might be possible to develop a new type of catalytic converter that will also prevent N_2O formation. However, this would require a significant R&D effort (de Jager *et al.*, 2001). N_2O emissions increase with the age of the catalyst in the converter. Although increased rate of replacement of catalytic converters will reduce N_2O emission, it is not a realistic measure because the cost would be prohibitively high (de Jager *et al.*, 2001). The catalyst performance can also be improved by having electrically heated catalyst, optimal positioning of the catalyst for accelerated heating, and catalytic insulation to keep catalytic converters hot for up to 24 hours. These technologies are already developed and mainly aim at reducing start-up emissions of NO_x and VOCs, little or no attention has been paid in the development and testing with regards to emission reduction of N_2O (de Jager *et al.*, 2001).

- Use of N_2O-decomposition catalyst – A future catalytic converter may consist of a traditional three-way catalyst (for NO_x CO and VOC), followed by a N_2O-decomposition catalyst. But there are technical obstacles to overcome. At this point, it is doubtful that the problems can be solved in the next few decades (de Jager *et al.*, 2001; US Climate Change, 2005).
- Use of alternative technologies for NO_x-emission reduction – Use of the three-way catalysts is not the sole option for reducing NO_x emissions. Increased use of low-VOC and low-NO_x engines may replace the traditional three-way catalyst controlled engines. Consequently, N_2O emissions from three-way catalysts can be avoided (de Jager *et al.*, 2001).
- Alternative fuel – Technological breakthroughs, such as fuel cell, will also greatly reduce the level of NO_x emissions (Lucas *et al.*, 2006). Fuel substitutes, such as use of hybrid, electric, ethanol, and natural gas vehicles, will also reduce N_2O emissions.

Given the high uncertainties and the R&D still needed to better understand the performance of catalysts and alternative technological options, not much additional practical information was found from the literature search.

3.2.2 – Stationary Combustion

Stationary combustion includes all the combustion activities except waste incineration, transportation (mobile combustion), and biomass burning for non-energy purposes. For stationary sources, nitrous oxide may result from the incomplete combustion of fuels. In the USEPA GHG inventory report, the sectors for N_2O emissions from stationary sources are categorized into five groups. The amounts of emissions from these five sub-sectors in 2004 were (USEPA, 2006a):

Electric power:	9.4 $MMT_{CO2\text{-}Eq.}$
Industrial:	3.0 $MMT_{CO2\text{-}Eq.}$
Commercial:	0.3 $MMT_{CO2\text{-}Eq.}$
Residential:	0.8 $MMT_{CO2\text{-}Eq.}$
US territories:	0.1 $MMT_{CO2\text{-}Eq.}$

Nitrous oxide emissions from stationary combustion are closely related to fuel types (coal, fuel oil, natural gas, or wood) and characteristics, combustion temperatures, and characteristics of pollution control equipment, and ambient environmental conditions. In general, lower combustion temperatures cause higher N_2O emissions. Emissions also vary with operation and maintenance practices (USEPA, 2006a; CARB, 2004). The N_2O emissions from stationary combustion in California were 0.19 $MMT_{CO2\text{-}Eq.}$ in 2004, which is 0.6% of the state's total N_2O emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (see Table 3.1).

Emission concentrations of N_2O from burning of fossil fuels in stationary combustion processes are low, typically 1 to 2 ppmV for coal-fired plants and 1 ppmV or less for oil- and gas-fired plants. Sources with higher emission concentrations are flue gases from fluidized bed combustion (FBC), flue gases from the selective non-catalytic reduction (SNCR) process, and combustion of wood, waste, and other biomass (de Jager *et al.*, 2001). Technological options for emission reduction of N_2O may be categorized into three groups: (1) reduced emissions from fluidized bed combustion; (2) use of selective catalytic reduction; and (3) fuel shift and reduction in fossil fuel consumption (de Jager *et al.*, 2001; de Soate, 1993; EC, 2001).

- Fluidized bed combustion (FBC) – Fluidized bed combustion has a higher energy conversion than conventional pulverized fuel combustion, and it has lower NO_x emissions due to a lower combustion temperature. However, the lower combustion temperature, between 800 and 900 ^{o}C, leads to higher N_2O emission concentrations, in the range of 30-150 ppmV. Several technological measures to reduce N_2O emissions are potentially available: (1) optimizing operating conditions, (2) using reversed air staging, (3) use of afterburner, (4) use of catalytic reduction, and (5) use of pressurized fluidized bed (de Jager *et al.*, 2001; IEA, 2000). It was estimated in an EU report, for applications of these technologies at FBC facilities, the cost is approximately $\$59/MT_{CO2\text{-}Eq.}$ for installing the gas afterburner, $\$51/MT_{CO2\text{-}Eq.}$ for reverse air staging, and $\$170/MT_{CO2\text{-}Eq.}$ for "optimized" operating conditions coupled with the use of catalytic control (IEA, 2000). It should be noted that these cost estimates were based on a very limited set of studies.

- Use of selective catalytic reduction – Use of selective non-catalytic reduction (SNCR) for reducing NO_x emissions requires higher operating temperatures, but it also creates N_2O emissions. An alternative NO_x abatement system may be selective catalytic reduction (SCR), which is considered preferable with regards to N_2O emission reduction; however, the specific cost of NO_x abatement of SCR is twice as expensive than the cost of SNCR (de Jager *et al.*, 2001). It should be noted here that some consider SCR effective in reduction of N_2O emissions while the others hold an opposite view (USEPA 2006a; Smit *et al.*, 2001)
- Fuel shift and reduction of fuel consumption – A shift from coal to oil or gas would result in lower N_2O emissions from fuel combustion. Reduction in fossil fuel consumption can be achieved, for example, by applying energy-efficiency improvement measures, applying energy saving measures, and increasing use of renewable energy. A shift to non-fossil energy source will further reduce the emissions. However, it is very unlikely that these options will be implemented as part of a N_2O abatement option (de Jager *et al.*, 2001; IEA, 2000).

3.2.3 – Municipal Solid Waste Combustion

About 7 to 17% of the municipal solid wastes (MSW) in the United States are managed by combustion. Almost all combustion of MSW occurs at waste-to-energy facilities where energy is recovered, while N_2O is a by-product of the combustion process (USEPA, 2006a).

Nitrous oxide emissions from this sector depend on a variety of factors, including types of waste as well as combustion temperature. N_2O emissions from MSW combustion in the United States were 0.5 $MMT_{CO2\text{-}Eq.}$ in 2004 (USEPA, 2006a). Nitrous oxide emissions from MSW combustion in California were 0.02 $MMT_{CO2\text{-}Eq.}$ in 2004, a very small fraction of the state's total N_2O emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (CEC, 2006). Overall, waste incineration is a relatively minor source of N_2O emission. The emission from this sector can be effectively reduced from source reduction, reuse, and recycling of municipal solid waste (IEA, 2000).

3.3 – Industrial Processes

In California, nitric acid production is the only industrial process that generates a reportable amount of nitrous oxide emissions, based on the most recent CEC inventory report (CEC, 2006).

3.2.1 – Nitric Acid Production

Nitric acid (HNO_3) is used in production of synthetic fertilizers, adipic acid, and explosives. Virtually all of the nitric acid production in the United States is manufactured by the catalytic oxidation of ammonia. During this reaction, N_2O is formed as a by-product and is released from reactor and vented into the atmosphere (USEPA, 2006b).

The United States N_2O emissions from nitric acid production were 16.6 $MMTCO_2$ in 2004, which is 7% lower than in 1990 (USEPA, 2006a). The nitrous oxide emissions from nitric acid production in California were 0.15 $MMT_{CO2\text{-}Eq.}$ in 2004, a very small fraction of the state's total nitrous oxide emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (CEC, 2006).

The nitric acid industry in the United States uses non-selective catalytic reduction (NSCR) or selective catalytic reduction (SCR) to control NO_x emission. In the process of destroying NO_x, NSCR systems are also very effective in destroying N_2O. However, only approximately 20% of the nitric acid plants use NSCRs because of the high energy costs and associated high gas temperature. The remaining 80% use SCR or extended absorption: neither of them is known to reduce N_2O emission (USEPA, 2006a).

The reduction of N_2O emissions can be achieved by optimizing the catalytic oxidation of ammonia in nitric production, by decomposing N_2O either during the processing of nitric acid or in the tail gas, or reduce the demand of nitric acid (by reducing the use of fertilizers). The parameters affecting the optimization of the nitric acid production including temperature, pressure, reaction time, and type of catalytic converter. Optimization of these parameters with respect to minimal N_2O formation is an option that is hard to quantify and it would affect the production efficiency, NO_x emission, and/or production costs. The potential and side-effects of this option need to be carefully evaluated. An estimate of the emission reduction potential and the corresponding cost can yet not be made (de Jager *et al.*, 2001). Reducing the demand of nitric acid is more a management issue, and it is out of scope of this project.

Currently, the N_2O destruction technologies include extending the reaction process through thermal decomposition or catalytic reduction in the reaction chamber, using NSCR or SCR in the upstream tail gas expander, or using SCR in the downstream tail expander (Smit *et al.*, 2001). The viable technological options are discussed in more details below:

- High-temperature catalytic reduction – N_2O concentrations in flue gases of nitric acid plants typically range from 300 to 1,700 ppmV. This range is generally more suitable for catalytic conversion than for direct incineration because of less energy input (de Jager *et al.*, 2001). This abatement option has several variations developed by different companies, such as BASF, Grand Paroisse, Norsk Hydro, and HITK, all involving the decomposition of N_2O into nitrogen and oxygen using various catalysts. The average estimated reduction efficiency is approximately 90% (USEPA, 2006b; IEA, 2000 & 2003).
- Low-temperature catalytic reduction – These systems work similarly to high-temperature counterparts, but they do not require additional heat to decompose N_2O. Some versions of this abatement require propane addition to the gas stream before undergoing the reaction process. The average estimated reduction efficiency is approximately 95% (USEPA, 2006b; IEA, 2000 & 2003).
- Non-selective catalytic reduction (NSCR) – NSCR uses a fuel and a catalyst to consume free oxygen in the tail gas and to convert NO_x to elemental nitrogen. Since all oxygen must be consumed before NO_x is reduced, excess fuel must be used and result in methane emissions. NSCR can reduce N_2O emission by 80-90 percent (USEPA, 2006b; IEA, 2000 & 2003).
- Thermal decomposition – Direct thermal decomposition (afterburning) with fuel injection of natural gas or methane is generally not considered as a feasible option because of the relatively low off-gas concentrations of N_2O from nitric acid production. However, in some cases off-gases could be mixed with high-temperature off-gases of other near-by industrial processes, and it could result in a net reduction of N_2O. Reduction potential and costs are site-specific and not quantified in the literature (de Jager *et al.*, 2001).

- Photo-catalytic conversion – It was reported in 1920s that absorption of ultraviolet light of 158 or 185 nm would result in the dissociation of N_2O (Oonk, 1995). Neither reduction potential nor costs have been developed and research on its applicability to off-gases of nitric acid production is required (de Jager *et al.*, 2001).
- Biofiltration of off-gases using denitrifying bacteria – Nitrous oxide might be decomposed biologically. In this option, the N_2O is dissolved into water and subsequently converted to nitrogen and oxygen gases by denitrifying bacteria (Oonk, 1995). Neither reduction potential nor costs have been developed and research on its applicability to off-gases of nitric acid production is required (de Jager *et al.*, 2001).

Table 3.6 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from nitric acid production. Each method, seven in all, uses different catalysts to reduce N_2O to N_2 and O_2, through either high-temperature or low-temperature catalytic reduction methods or a non-selective catalytic reduction method. On average, these methods reduce N_2O emissions by 89% (Delhotal *et al.*, 2006). The nonselective catalytic reduction option is currently widely used at existing facilities, while the rest of options are presently still in experimental and R&D stages (IEA, 2003).

Table 3.6 – Technological Options for Nitric Acid Production

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
High-temp catalytic reduction (BASF)[1]	10	-	80	100	\$2.76	\$0.17	\$0.00
High-temp catalytic reduction (Grand Paroisse)[1]	10	-	77.6	100	\$3.09	\$0.16	\$0.00
High-temp catalytic reduction (HITK)[1]	10	-	100	100	\$3.18	\$0.22	\$0.00
High-temp catalytic reduction (Norsk Hydro)[1]	10	-	90	100	\$2.32	\$0.15	\$0.00
Low-temp catalytic reduction with propane addition[1]	10	-	95	100	\$3.64	\$1.81	\$0.00
Low-temp catalytic reduction (Krupp Uhde)[1]	10	-	95	100	\$3.45	\$0.20	\$0.00
Non-selective catalytic reduction[1]	20	-	85	100	\$6.29	\$0.16	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2000); IEA (2003); USEPA (2004)

3.4 – Solvent and Other Product Uses

Nitrous oxide is a clear, colorless, oxidizing gas with a slightly sweet odor. It is often used with oxygen in carrier gases to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. It is also commonly used as a propellant in pressure and aerosol products with pressure-packaged whipped cream as the largest application. Small quantities of nitrous oxide are also used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing

- Oxidizing agent used, with acetylene, in atomic absorption spectrometry
- Production of sodium azide, which is used to inflate airbags
- Fuel oxidants in auto racing
- Oxidizing agent in blow torches used by jewelers and others

Production of nitrous oxide in the United States was approximately 17 Giga-grams (Gg) in 2004, while the N_2O emissions were 15 Gg (4.8 $MMT_{CO2-Eq.}$). In other words, approximately 90% of the total production/usage ended up in the atmosphere. Production of N_2O has stabilized since 1990 because medical industries have found other alternatives for anesthetics. In addition, more medical procedures are being performed on an out-patient based using local anesthetics (N_2O is not required). Use of N_2O as a propellant for whipped cream has also stabilized due to the increase use of reusable plastic tubes in packaging of cream products (USEPA, 2006a).

Nitrous oxide emissions from this sector are not included in the recent California GHG inventory report by CEC (CEC, 2006). No practical technological options for reducing nitrous oxide emissions from this sector were found from the literature search.

3.5 – Land-use Change and Forestry

In California there are three relevant emission sources: (1) forestland remaining forestland, (2) settlement remaining settlement, and (3) forest fires.

3.5.1 – Forest Land Remaining Forest Land

The category of Forest Land Remaining Forest Land refers to forest areas that have been forests for at least 20 years. Less than 1% of the fertilizers applied to soils in the United States are added to the forest soils. Application rates are similar to those for the cropped soils, but in any given year, only a small proportion of total forest receives fertilizer. This is because the forests are typically fertilized twice in their entire 40-year growth cycle. The N_2O emissions from forest soils ranged from 0.1 to 0.5 $MMT_{CO2-Eq.}$ from 1990 to 2004 (USEPA, 2006a).

Nitrous oxide emissions from this sector are not included in the recent California GHG inventory report by CEC (CEC, 2006). No practical technological options for reducing nitrous oxide emissions from this sector were found from the literature search.

3.5.2 – Settlements Remaining Settlements

The category of Settlements Remaining Settlements refers to all classes of urban tree formations, focusing primarily on urban trees grown along streets, in gardens, and parks, in lands that have been in use as settlements. Of the fertilizers applied to soils in the United States, approximately 10 percent are applied to lawns, golf courses, and other landscaping occurring within the settled areas. Application rates are less than those on cropped soils, and, consequently, account for a smaller proportion of N_2O emissions per unit area. The N_2O emissions from this source were 6.4 $MMT_{CO2-Eq.}$ in 2004, which is 15% higher than in 1990. The increase is due to a general increase in the application of synthetic fertilizer.

Nitrous oxide emissions from this sector are not included in the recent California GHG inventory report by CEC (CEC, 2006). No practical technological options for reducing nitrous oxide emissions from this sector were found from the literature search.

3.5.3 – Forest Fires

Nitrous oxide emissions from this sub-sector are not included in the most recent inventory report by CEC. No specific technological options for emission reduction were found from the literature search.

3.6 – Waste

Waste management is one of the minor sources of N_2O emissions. The emissions can come from domestic wastewater and industrial wastewater.

3.6.1 – Domestic Wastewater (Human Sewage)

Domestic human sewage is either discharged directly, to an on-site (decentralized) wastewater treatment system, or discharged to a centralized wastewater treatment plant. Nitrification and denitrification (N/DN) processes may occur in wastewater treatment. Nitrogen compounds, such as urea, ammonia, and proteins, are converted to nitrate (NO_3^-) under aerobic nitrification. Denitrification occurs under anoxic conditions (absence of free oxygen, but presence of nitrate) and converts nitrate into nitrogen. N/DN, which is to remove nitrogen compounds from wastewater, is required for many municipal wastewater treatments. Nitrous oxide is an intermediate product of both nitrification and denitrification processes, but is more often associated with denitrification (USEPA, 2006a). Nitrous oxide emissions from municipal wastewater treatment, equipped with nitrogen removal, released about 0.001% of N-received as N_2O-N from the nitrification tanks and 0.04% of N-received as N_2O-N from the denitrification units (de Jager *et al.*, 2001).

In the United States, nitrous oxide emissions from domestic wastewater were 16 $MMT_{CO2\text{-}Eq.}$ in 2004 from the following two sources:

- Centralized wastewater treatment process (0.3 $MMT_{CO2\text{-}Eq.}$ in 2004)
- Emission from effluent that has been discharged into aquatic environments (15.8 $MMT_{CO2\text{-}Eq.}$ in 2004)

Nitrous oxide emissions from these activities in California were 1.07 $MMT_{CO2\text{-}Eq.}$ in 2004, 3.2% of the state's total nitrous oxide emissions, 33.3 $MMT_{CO2\text{-}Eq.}$ (see Table 3.1).

In contrast to methane emission reduction technologies, which are primarily focused on untreated wastewater and on-site small wastewater treatment plants, N_2O reduction should be more focused on N_2O emission from denitrification in large-scale, centralized plant (de Jager *et al.*, 2001). Under optimal operating conditions, N_2O formation can be reduced by up to one-third during nitrification and two-thirds during denitrification (IEA, 2000). Although no cost figures have been reported, it is expected that process optimization can be accomplished with negligible costs (Hendriks *et al.*, 1998). It has also been reported that, from comparisons of N_2O emission from several wastewater treatment processes, intermittent aeration in the nitrification/denitrification process is optimal with regards to reduction of N_2O emissions as well as high nitrogen removal (Inamori *et al.*, 2003). When nitrogen removal in wastewater treatment is not necessary and the application of wastewater sludge to agricultural land as a nitrogen source is allowable, the net N_2O emission from wastewater sector may be reduced (de Jager *et al.*, 2001).

3.6.2 – Industrial Wastewater

Nitrous oxide is an intermediate by-product of decomposition of organic nitrogen compounds, such as protein and urea, in industrial wastewater. N_2O generation and emission mechanisms are not well understood (IEA, 2000). No specific technological options for emission reduction were found from the literature search.

References

Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.

Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.

Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) “Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions”, *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.

Branosky, E.; Greenhalgh, S. (2007) “Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.

California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.

California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.

Church, S. (2007) Personal communication – reviewers’ comments on the Task 1 Report of this project on February 20, 2007, California Air Resources Board.

Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) “Global Estimates of Potential Mitigation of Greenhouse Gas Emissions by Agriculture”, *Nutrient Cycle in Agroecosystems*, 52, 221-228.

Dalal, R. C.; Wang, W.; Robertson, G.P.; Parton, W. (2003) “Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: a Review”, *Australian J. Soil Res.* 41, 165-195.

de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.

de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

de Soate, G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control”, in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.

DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) “Methane and Nitrous Oxide Mitigation in Agriculture’, *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 89-108.

Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.

Graus, W., Harmelink, M. and Hendriks, C. (2004) “Marginal GHG-Abatement curves for agriculture”, Ecofys, Utrecht, the Netherlands.

Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.

Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.

International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.

International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases – Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.

Kasper, G.J.; Holshof, G.; van den Pol-van Dasselaar, A. (2002) “Reduction of N_2O Emission by Introduction of Precision Fertilization”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.

Kowalenko, G. (1999) “Assessing Nitrous Oxide Emissions from Farming Practice”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.

Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.

Lemke, H.; Janzen, H.; Rochette, P. (1999) “Processes of Nitrous Oxide Emissions from Canadian Agroecosystems”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.

Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.

McTaggert, I. P.; Clayton, H.; Smith, K.A. (1994) “Nitrous Oxide Flux from Fertilized Grassland: Strategies for Reducing Emissions”, in Non-CO_2 Greenhouse Gases: Why and How to Control, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.

Moritomi, H.; Mochida, I. (2000) “N_2O Emission Inventory and the Abatement Technologies in Japan”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.

Mosier, A.R.; Duxbury, J.M.; Freney, J.R.; Heinemeyer, O.; Minami, K. (1998) “Assessing and Mitigating N_2O Emissions from Agricultural Soils”, *Climatic Change*, 40, 7-38.

O’Hara, P.; Freney, J.; Ulyatt (2003) “Abatement of Agricultural Non-carbon Dioxide Greenhouse Gas Emissions – A Study of Research Requirements”, a report prepared for the Ministry of Agriculture and Forestry, New Zealand.

Oonk, J. (1995) “Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control”, Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.

Smit, A.W.; Gent, M.M.C.; van den Brink, R.W. (2001) “Market Analysis DeN_2O: Market Potential for Reduction of N_2O Emissions at Nitric Acid Facilities”, Leiden, Netherlands: Jacobs Engineering Nederland.

Tsuruta, H.; Akiyama, H. (2000) “NO and NO_2 Emissions with Application of Different Types of Nitrogen Fertilizer”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.

U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

U.S. Environmental Protection Agency (2001) “U.S. Adipic Acid and Nitric Acid N_2O Emissions 1990 – 2020: Inventories, Projections and Opportunities for Reductions (draft)” Office of Atmospheric Programs, United States Environmental Protection Agency, November, 2001.

U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.

U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).

U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.

U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Wikipedia (2007) “Nitrous Oxide”, http://en.wikipedia.org/wiki/Nitrous_oxide.

Worrell, E. (1994) “Potentials for Improved Use of Industrial Energy and Materials”, Utrecht University, Faculteit Scheikunde, the Netherlands.

CHAPTER 4

HIGH-GWP GASES

4.0 – Introduction

Hydrofluorocarbons (HFCs) and, to a lesser extent, perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODS) that have been or are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990; however, these compounds, along with sulfur hexafluoride (SF_6), are potent greenhouse gases with high global warming potentials (GWP). The GWPs of these gases range from 120 to 22,200 times the global warming capability of CO_2 over a 100-year time horizon and they have long life spans in the atmosphere, in some cases for hundreds and thousands of years (USEPA, 2001; IPCC, 2001).

Other emission sources of these high-GWP gases in the United States include HCFC-22 production, electrical transmission and distribution systems, semiconductor manufacturing, aluminum production, and magnesium production and processing (USEPA, 2006a).

Table 4.1 summarizes the emissions of high-GWP gases from various sectors in California and in the United States. The data were extracted from the recent inventory reports of USEPA and CEC (USEPA, 2006a; CEC 2006). As shown, emissions of high-GWP gases in California account for approximately 9.9% of the nationwide emissions of high GWP-gases. Substitution of ODS is the dominant emission source of high-GWP gases in California and in the USA; 88.8% and 72.3% of total emissions, respectively. Electrical transmission and distribution (7.2%) and semiconductor manufacture (4.0%) are the other two significant emission sources of high-GWP gases in California. There are no manufacturing activities of HCFC-22 and aluminum, and few activities of magnesium in California; consequently, the discussions on technological options for emission reduction of high-GWP gases in this chapter will focus on three sectors: substitution of ODS, electrical transmission and distribution, and semiconductor manufacture. The percentage emissions of major sources in the USA and California are also plotted, in a descending order, in Figures 4.1 and 4.2, respectively.

Table 4.1 – Summary of Emissions of High-GWP Gases in the USA and California

	USA (2004)		**California (2004)**		
Source	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**MMT$_{CO2\text{-}Eq.}$**	**(%)**	**CA/USA**
Substitution of Ozone Depleting Substances	103.3	72.3%	12.61	88.8%	12.2%
HCFC-22 Production	15.6	10.9%	-	-	-
Electrical Transmission and Distribution	13.8	9.7%	1.02	7.2%	7.4%
Semiconductor Manufacture	4.7	3.3%	0.57	4.0%	12.1%
Aluminum Production	2.8	2.0%	-	-	-
Magnesium Production and Processing	2.7	1.9%	-	-	-
Total	**142.9**	100%	**14.2**	100%	**9.9%**

Figure 4.1 – Major Sources of High-GWP Gases Emissions in the USA

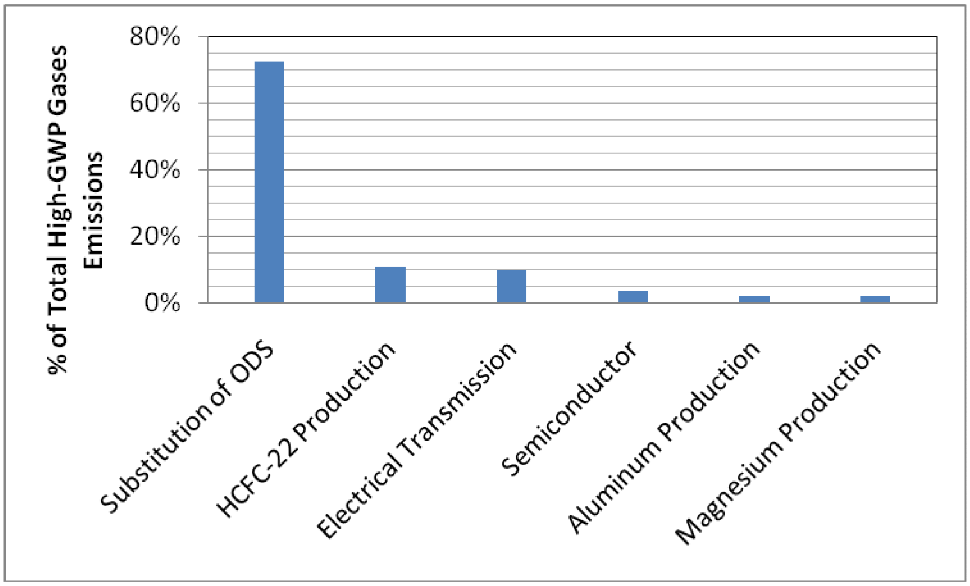
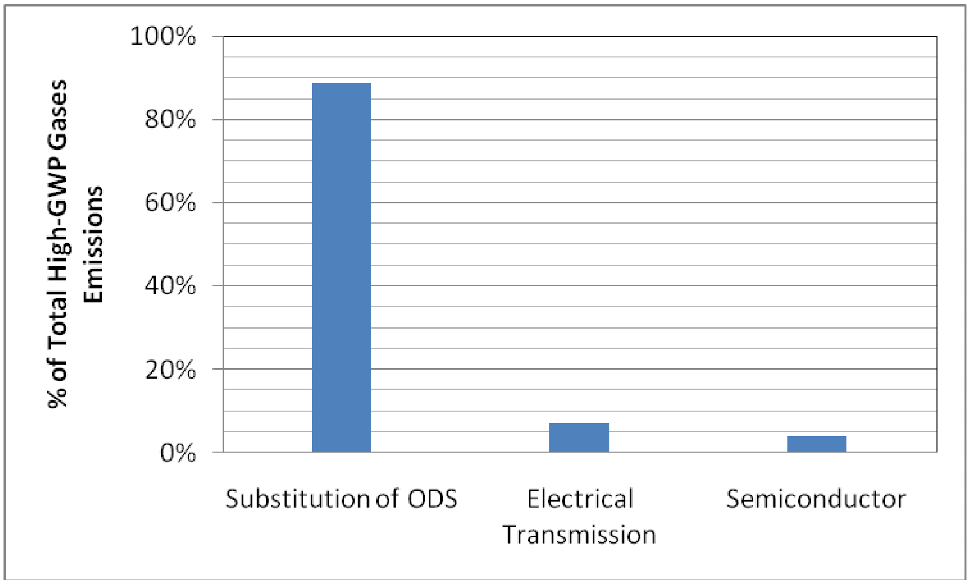


Figure 4.2 – Major Sources of High-GWP Gases Emissions in California



There are three significant differences between these high-GWP fluorinated compounds (HFCs, PFCs, and SF_6) with the other major greenhouse gases (CO_2, CH_4, and N_2O). Unlike other greenhouse gases, the fluorinated gases have few or no natural sources. Most of the end-uses of these fluorinated compounds are in enclosed systems so that their potential emissions can occur years after production and consumption, but emissions reductions through containment, recovery, and recapture are feasible. Most of these fluorinated compounds are for use in applications that use large amount of energy; thus, the energy efficiency becomes an important factor in considering options for their emission reductions (McFarland and van Gerwen, 2000).

4.1 – Substitution of Ozone Depleting Substances

Use of HFCs has allowed the rapid phase-out of halons, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs). HFCs are generally selected for applications where they can provide superior reliability or safety (e.g., low toxicity and flammability). They are used in various industrial applications including the following (USEPA, 2001; USEPA, 2004; USEPA, 2006a):

- Refrigeration and air conditioning equipment
- Solvent cleaning
- Foam production
- Sterilization
- Fire extinguishing
- Aerosols

PFCs have also been introduced as ODS substitutes in a smaller number of applications, specifically in very limited refrigeration and fire protection applications (USEPA, 2001). HFCs and PFCs are not harmful to the stratospheric ozone layer, but they are potent greenhouse gases. Their emissions to the atmosphere are increasing from small amounts in 1990 to 103.3 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$ in 2004 in the United States. In 1990 and 1991, the only significant emissions of HFCs and PFCs were relatively small amounts of HFC-152a (a component of the refrigerant blend R-500 used in chillers) and HFC-134a in refrigeration end-uses. Starting from 1992, use of HFC-134a increased as a refrigerant in motor vehicle air conditioners and in refrigerant blends such as R-404A. In 1993, the use of HFCs in foam production and as an aerosol propellant began, and in 1994 these compounds also found applications as solvents and sterilants. The increasing trend is expected to continue in the near term and will accelerate over the next decade as HCFCs, interim substitutes for CFCs in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol* (USEPA, 2006a).

Out of the 103.3 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$ emissions in 2004, the end-use sectors that contribute most toward emissions of HFCs and PFCs as ODS substitutes in the United States include (USEPA, 2006a):

- Refrigeration and air conditioning (88.4 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$) – 85.6%
- Technical aerosols (11.1 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$) – 10.7%
- Solvents (1.6 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$) – 1.5%
- Foams
- Fire extinguishing
- Sterilization

The emissions of high-GWP gases as ODS substitutes in California were 12.61 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$ in 2004; they represented 89 % of the state's total emissions of high-GWP gases, 14.2 $\mathrm{MMT}_{\mathrm{CO2\text{-}Eq.}}$ (see Table 4-1).

4.1.1 – Refrigeration and Air Conditioning

The emissions of HFCs and PFCs from refrigeration and air conditioning account for the majority (~85%) of their emissions from the sector of ODS substitutes in the United States. In refrigeration and air-conditioning, the dominant technology is the cold vapor compression cycle; HFCs and PFCs are used as the fluids (refrigerants) for this cycle, mainly because of their non-flammability and good thermodynamic properties. In this section the technological options for emission reduction of high GWP gases from these applications will be discussed in general first, their specific applications to various end-uses will follow. The technological options can be grouped into the following categories:

- Refrigerant options – Some "natural refrigerants", such as hydrocarbons (HCs) or ammonia, with no or low GWP can be alternative substitutes. Carbon dioxide is another alternative (IEA, 2001).

  Ammonia has excellent thermodynamic properties and can be used in many types of refrigeration and air-conditioning systems. Efficiencies of chillers using ammonia as a refrigerant are as good as or better than those using HFC-134a. However, due to its toxicity and slight flammability, building and fire codes restrict the use of ammonia in the urban areas of the United States; they limit the potential for expanded use of ammonia in chillers (Sand *et al.*, 1997) and in the refrigeration units within public spaces such as supermarkets (Cooper, 1997). Although the safety concerns can be alleviated by adequate engineering design such as secondary loops and isolation, the high initial capital cost and regulatory compliance make the wide use of ammonia unlikely in the near future (USEPA, 2001). Ammonia in the presence of water cannot be used with copper or zinc (UNEP, 1999a), therefore compatible components would have to be used, especially for commercial unitary air-conditioning systems, which commonly use copper for the refrigerant tubing in the heat exchangers and in other components (USEPA, 2001).

  As a refrigerant, hydrocarbons have good thermodynamic properties, high energy efficiencies, and low GWP, but their flammability results in significant safety and liability concerns. Addressing these concerns will increase costs incurred from design changes, such as relocation of electrical components to reduce the likelihood of accidents from potential leaks (Kruse 1996; Paul, 1996) and additional hardware costs (A.D. Little, 1999). Systems using flammable hydrocarbons as refrigerants will require additional engineering and testing, development of standards and service procedures, and training of manufacturing and service technicians before commercialization (USEPA, 2001).

  Some companies outside the United States have begun testing systems with flammable hydrocarbons and these systems could be installed in vehicles in the near future (Mathur, 1996; Baker, 2000). Outside the automotive applications, one company in the United Kingdom has developed four blends of hydrocarbon refrigerants (composed of isobutane, propane, and ethane) for various residential, commercial, and industrial refrigeration and air-conditioning systems. The world's largest industrial refrigeration company, which is located in Sweden, is now using these hydrocarbon refrigerants in a full range of chillers, which require 60% less refrigerant charge than with HFCs (USEPA, 2001). One large refrigerator manufacturer also converted its U.K. factory to use these hydrocarbon refrigerants. There are many hydrocarbon refrigerators in use in Europe (BOC Gases Ltd., 2007). Several refrigerant blends that contain less than 5% of hydrocarbons have been approved in motor vehicle air conditioners under EPA's Significant New Alternatives Policy Program (USEPA, 2001).

  In addition to its low GWP, CO_2 is advantageous because it is generally available at a cost, only 20% greater than the conventional systems (Baker, 1998). However, main concerns are safety, design cost, capital cost, potential loss of operational efficiency, refrigerant containment, long-term reliability, and compressor performance (Environment Canada, 1998). Transcritical carbon dioxide systems are under development by many vehicle manufacturers. These systems require substantial new engineering and test efforts, with emphasis on reliability testing (Wertenbach, 1996). The efficiency of transcritical CO_2 cycle is equivalent to HCFC-22 cycle (UNEP, 1998; IEA, 2001). Training is required to safely repair these systems because operating pressures are up to six times higher than they are in systems with HFC-134a. The first systems could be available in the near future (Baker, 2000).

- Alternative technologies – There are a number of alternative technologies mentioned in literature. Most of them are under evaluation and are not available as commercial products in a wide range soon; they include Joule-Brayton air cycle, Stirling cooling engines, Peltier coolers, thermo-acoustics, electro-osmosis, evaporative cooling, and thermoelectric refrigeration (van Gerwin and Vervoerd, 2000; IEA, 2001). Cooling with the thermoelectric effect has low efficiency in conjunction with high initial cost. Stirling cycles are mainly used for cryogenic cooling due to their high initial costs. Although refrigeration with thermo-acoustic effects in principle is very simple, it is only commercially used in cryogenic cooling. Refrigeration can also be realized using electro-osmosis effect by connecting an electrical current to a membrane; but it is still in the R&D stage (IEA, 2001). Other technological options such as oil-free compressors and geothermal cooling systems were also mentioned in literature but detailed analyses were not available because of their low applicability in future markets (USEPA, 2004). More practical and viable approaches are secondary-loop systems and distributed systems. Desiccant cooling, absorption chillers and refrigerators, and heat pumps are also available (USEPA, 2001).

  Secondary-loop systems circulate a secondary coolant, such as liquid ice or brine, from the central refrigeration system to the display cases, thereby operating at reduced charges and lower leakage rates. They can allow the use of flammable or toxic refrigerants such as ammonia and hydrocarbons. The primary disadvantage of the secondary-loop system is its low energy efficiency; however, installers of the secondary-loop systems suggest that decreased charge sizes, decreased leak rates, lower maintenance requirement, and longer shelf life can result in significant cost-saving over time (USEPA, 2001). In addition, technological advancements, such as high-efficiency evaporative condensers and display cases with high temperature brine, have increased system efficiency. These new improvements are commercially available, but still very costly (Walker, 2000). The secondary loops are potentially applicable for motor vehicle air-conditioning and residential unitary end-uses (USEPA, 2001).

  Distributed refrigeration puts refrigeration equipment closer to the food display cases they serve and reduces the excessive refrigerant piping (US Climate Change, 2005). Refrigerant charges for a distributed system can be smaller than that used in a comparable conventional direct expansion system. Reduced charge sizes and increased energy efficiency could effectively decrease global warming impacts (Sand *et al.*, 1997).

  In desiccant cooling, a desiccant removes air moisture and the dry air is then cooled. Desiccant cooling may replace the latent cooling by coolers and motor vehicle air conditioners. Desiccant is thermally regenerated. New automobiles are energy efficient and do not produce enough waste heat to regenerate desiccants; therefore, it is only feasible where there is a large heat source as in a truck or bus (Environment Canada, 1998; USEPA, 2001). An auxiliary burner can be added for desiccant regeneration; more research is needed to improve the size, weight, durability, life expectancy, and initial cost of current prototypes (Fischer *et al.*, 1994). Integrated desiccant cooling systems that combine a desiccant cooling system with vapor compression or other cooling systems have been successful in some commercial buildings. They are suitable for locations requiring precisely-controlled and/or low humidity such as supermarkets and hospital operating rooms (Fischer *et al.*, 1994).

Gas-fired absorption water chillers are available in the United States and are common in Japan where electricity costs are high and waste heat is available. They will be acceptable to the end-users only when low cost natural gas or waste heat are available to off-set the high capital cost. Direct-fired three-effect absorption chillers, which are more efficient than the current two-effect units, are currently under development by U.S. companies (Sand *et al.*, 1997).

More than one million thermally-activated ammonia/water absorption refrigerators were sold worldwide by 2001 and their refrigerants have negligible GWP. They are commonly used in hotel rooms and for recreational vehicles because of quiet operation and ability to use bottled gas as an energy source, but they are limited in size due to design constraints (USEPA, 2001).

Absorption heat pumps that would be used for heating and cooling in residential and light commercial applications are being developed worldwide. Use of absorption heat pumps can reduce global warming impacts in areas where heating load dominates; however, it would have the opposite effect where cooling load dominates (Sand *et al.*, 1997).

- Leakage control – Reducing leaks, recovering and recycling refrigerants during servicing, and capturing, recycling, or destroying refrigerant at decommissioning of equipment have led to significant emission reductions in this sector (McFarland and van Gerwen, 2000). There are many leak reduction approaches available, ranging from simple repairs of short duration to major, long-lasting system repair jobs (USEPA, 1998). Replacement of high-emitting fittings is one of the most technically and economically feasible approaches that can be used to reduce refrigerant leakage (USEPA, 2001).
- Recovery and recycling – Recovery involves use of a device that transfer refrigerant to an external storage container prior to servicing of the equipment, and the recovered refrigerant may then be recharged back to the equipment, cleaned through the use of recycling devices, sent to a reclamation facility to be purified, or disposed of through incineration.
- Proper refrigerant disposal – One potential emission source is the accidental venting of contaminated refrigerant. One method to reduce venting of such refrigerant is to increase reclamation of waste refrigerant and properly dispose of the refrigerant that cannot be reclaimed (UNEP, 1999a). Proper refrigerant disposal is required by existing law (USEPA, 2001); if it is not adequately enforced, it may be a significant emission source.

In the United States, the refrigeration and air-conditioning sector includes nine major end-uses (USEPA, 2004):

- Household refrigeration
- Residential air-conditioning and heat pumps
- Motor vehicle air-conditioning (MVAC)
- Chillers
- Retail food refrigeration
- Cold storage warehouse
- Refrigerated transport

- Industrial process refrigeration
- Commercial unitary air-conditioning systems

Household refrigeration. The household refrigeration end-use consists of household refrigerators and freezers. They usually utilize the cold vapor compression cycle. The system typically consists of a hermetically-sealed circulation loop that contains the refrigerant and connects an evaporator, a condenser, and a compressor. Refrigerant loss occurs mainly due to mechanical damage of the evaporator coil; minor loss can also occur during the manufacturing process while charging the refrigerant (IEA, 2001). Although this end-use is one of the largest in terms of the number of units in use (more than 150 million household refrigerators in the United States), the emissions are small because of their small charge sizes (typically 0.32 kilograms/unit), infrequent requirement for recharge, and low leakage rate. The retirement of old refrigerators is also not expected to result in significant HFC emissions, as U.S. regulation requires the refrigerants be recovered from appliances before disposal (USEPA, 2001).

Although the potential of HFC emission from this end-use is relatively small, there are many technological options for emission reduction available. Hydrocarbons have the same good thermal properties as HFCs; however, the flammability of the hydrocarbons makes redesigns in the manufacturing process necessary. Since the handling of the refrigerant mainly takes place at the manufacturing site, the conversion to hydrocarbon in hermetic systems has proved easier than expected. Consequently, approximately 45% of new household refrigeration equipment uses hydrocarbon as the refrigerant in Europe. In Northern Europe, essentially all new appliances are charged with hydrocarbons (IPCC, 2000).

Table 4.2 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from household refrigeration. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.2 – Technological Options for Household Refrigeration

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	1-3	\$26.19	\$3.40	\$1.69
Use of hydrocarbons[2]	15	-	100	2-7	\$38.49	\$0.00	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}eq.}$
1: CEC (2005); 2: IEA (2003)

Residential air-conditioners and heat pumps. Residential air-conditioning and heat pumps are another source of HFCs emissions from the residential sector. Building air conditioning (AC) systems are distinguished in small (typically room AC systems), indirect cooling or secondary chiller systems, and centralized direct exchange (DX) systems. Heat pumps use the cold vapor compression cycle to absorb heat at a low temperature level and transfer it to a higher temperature level. Most of these units are window units and central air conditioners. Carbon dioxide is under research as an alternative fluid for heat pumps (IEA, 2001). Smaller units for residential use with hydrocarbon are available from manufactures in Northern Europe (UNEP, 1998). Leak repair and refrigerant recovery/recycling are considered as viable technological options for this end-use (IEA, 2003; CEC 2005).

Table 4.3 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from residential air-conditioners and heat pumps. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.3 – Technological Options for Residential Air-conditioners and Heat Pumps

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	-	10	95	10	$26.19	$3.40	$1.69
Leak repair[2]	5	5	90	0.2-0.5	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005); 2: IEA (2003) & USEPA (2001)

Motor vehicle air-conditioning (MVAC). Motor vehicle air-conditioners refer to the AC systems contained in motor vehicles. Refrigerant use in this sector is significant because there are more than 160 million motor vehicles with operational air conditioners in the United States, each contains approximately one kilogram of refrigerant (USEPA, 2001). Although high losses in leaks and maintenance have been reduced from 30 to 10% due to better design and staff training (Öko-Recherche, 1999), leakage rates are still much higher than those of household refrigeration units or equivalent hermetic systems because the vehicle engine needs to transmit mechanical energy to the compressor with a drive shaft. Ammonia, hydrocarbon, CO_2, and Joule-Brayton air-cycle alternatives for buses are under examination (UNEP, 1998). In some cases, despite its poor energy efficiency, the air-cycle is used for air conditioning in trains (e.g., the first generation German high speed trains) due to its robustness (IEA, 2001). The European Union Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) Project has evaluated the applicability of the transcritical CO_2 cycle and found it promising. Several car manufacturers have started development of this technology and expect commercialization between 2005 and 2008 (IEA, 2001). Two additional technology options were considered in the analysis for MVACs: improved HFC-134a systems and HFC-152a systems (CEC 2005, USEPA, 2006b). Due to improvements in construction and dimensions of the flexible hose, connections of the system components, and compressor shaft seals, the improved HFC-134a systems can reduce direct emissions from regular leakage by 50% (CARB, 2004). The use of HFC-152a as a drop-in replacement for HFC-134a can reduce total emissions by 89% as a result of its lower GWP. It is assumed that this option will become available in 2012 (CEC, 2005). Refrigerant recovery reportedly is also a viable technological option for emission reduction in this sector (IEA, 2003).

Table 4.4 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from MVACs. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.4 – Technological Options for Motor Vehicle Air Conditioners

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	10	\$26.19	\$3.40	\$1.69
Improved HFC-134a systems[2]	-	1	18	15	\$404.80	\$0.00	\$168.30
HFC-152a systems[2]	-	0	89	15	\$192.33	\$0.00	\$54.15
Use of CO_2[1]	12	0	100	15	\$611.97	\$0.00	\$86.03

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & IEA (2003); 2: CEC (2005)

Chillers. Chillers are used to regulate temperature and humidity in large buildings (i.e., offices, hotels, and shopping centers). Depending on the type of compressor employed, there are three primary types of chillers: centrifugal, reciprocating, and screw. The charge size of a chiller ranges from 25 (reciprocating) to 1,800 (centrifugal) kilograms. Large capacity screw and centrifugal chillers account for over 150,000 units in the United States (USEPA, 1998). Relative to most AC and refrigeration equipment, chillers are built for longer service lifetime (USEPA, 2001). Leak repair is considered as a viable technological option for emission reduction in this sector (IEA, 2003).

Table 4.5 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of the technological option for emission reduction from chillers. More detailed description and analyses of this technological option can be found in Appendix C.

Table 4.5 – Technological Options for Chillers

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	5	90	0-4	\$27.55	\$0.00	\$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Retail food refrigeration. It includes refrigerated equipment found in food service establishments such as supermarkets, convenience store, and restaurants. There are about 1.6 million retail food refrigeration systems in the United States with charge sizes ranging from 6 to 1,800 kilograms (EPA, 1998). Annual emission rates are estimated to fall in the range from 15 to 30% (UNEP, 1998) for direct expansion systems; new installations after 1998 can exhibit loss rates at around 3% if carefully designed and maintained (Ecofys, 1999). Distributed refrigeration systems offer the ability to reduce the refrigerant charge and minimize the need for a dedicated mechanical room containing multiple compressor racks (IEA, 2003). Systems with secondary loops for the warm or the cold side of the refrigeration process can also reduce the needed charge and the leakage (A.D. Little, 1999).

Alternative systems, such as using CO_2, ammonia, hydrocarbons, or a combination of them as refrigerants, can be used, but the capital cost is high (IEA, 2003). Hydrocarbons and ammonia are best used in decentralized refrigeration units with secondary carrier loops (IEA, 2001). Because these systems isolate customers from the refrigerant, ammonia and hydrocarbons can be used (EPA, 2001).

Table 4.6 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from retail food refrigeration. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.6 – Technological Options for Retail Food Refrigeration

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Leak repair[1]	5	10	90	6-15	$27.55	$0.00	$3.05
Alternative systems[2]	15	-	100	11-31	$188.10	-$1.41	$2.76
Ammonia secondary loop systems[1]	20	10	100	11-31	$115.98	$12.89	$1.58
HFC secondary loop systems[1]	20	10-20	100	11-31	$30.93	$12.89	$1.58
Replacing direct expansion systems with distributed systems[1]	20	10-20	100	11-31	$82.15	-$6.84	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001); 2: IEA (2003)

Cold storage warehouse. They are used to store perishable goods such as meat, produce, and dairy products. There are about 2,000 cold storage warehouses in the United States with charge sizes of about 4,000 kilograms (EPA, 1998a). The technological options for reducing emissions are very similar to those for retail food refrigeration in principle, but with different levels of technical applicability.

Table 4.7 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from cold storage warehouse. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.7 – Technological Options for Cold Storage Warehouse

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Leak repair[1]	5	10	90	3-14	$27.55	$0.00	$3.05
Alternative systems[2]	15		100	6-27	$188.10	-$1.41	$2.76
Ammonia secondary loop systems[1]	20	10	100	6-27	$115.98	$12.89	$1.58
HFC secondary loop systems[1]	20	10-20	100	6-27	$30.93	$12.89	$1.58
Replacing direct expansion systems with distributed systems[1]	20	10-20	100	6-27	$82.15	-$6.84	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001); 2: IEA (2003)

Refrigerated transport. This end-use includes refrigerated ship holds, truck trailers, railway freight cars, and other shipping containers. The end-use is relatively small because the average charge sizes are relatively small, 7 to 8 kilograms, and less than one million units are currently in use in the United States (USEPA, 2001). Leakage rates are estimated to be around 5% for rail transport and 15% for road transport (Öko-Recherche, 1999). Potential refrigerant alternatives with lower GWP would be hydrocarbons, ammonia, and CO_2. However, safety legislation may prohibit the use of flammable or toxic fluids in many applications, which excludes hydrocarbons and ammonia (IEA, 2001). Refrigerant recovery/recycling is considered as a viable technological option for emission reduction (IEA, 2003).

Table 4.8 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of the technological option for emission reduction from refrigerated transport. More detailed description and analyses of this technological option can be found in Appendix C.

Table 4.8 – Technological Options for Refrigerated Transport

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	10	$26.19	$3.40	$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industrial process refrigeration. It includes complex refrigeration systems used in the chemical, petroleum, pharmaceutical, oil and gas, and metallurgical industry as well as sports and leisure facilities. There are approximately 7,000 industrial process refrigeration systems in the United States with charge sizes ranging from 650 to 9,100 kilograms (EPA, 1998). Ammonia and the cold vapor compression cycle have dominated this end-use. Hydrocarbons are also used in locations where the handling of flammable chemicals is a common practice. Another potential technology alternative is the use of water as a refrigerant (IEA, 2001). The air cycle is also occasionally used for food freezing and liquefied gas production (van Gerwen and Vervoerd, 2000).

Table 4.9 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from industrial process refrigeration. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.9 – Technological Options for Industrial Process Refrigeration

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	10	90	1-5	$27.55	$0.00	$3.05
Alternative systems[2]	15	-	100	2-9	$188.10	-$1.41	$2.76
Ammonia secondary loop systems[1]	20	10	100	2-9	$116	$12.89	$2.76

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}eq.}$
1: IEA (2003) & USEPA (2001); 2: IEA (2001) & IEA (2003)

Commercial unitary air-conditioning. There are approximately 2.5 million commercial unitary air-conditioning units in use in the United States with relatively small charge sizes ranging from 9.5 to 34 kilograms (USEPA, 1998a). Leak repair and refrigerant recovery and recycling are considered as viable technological options for emission reduction from this end-use (IEA, 2003; CEC 2005).

Table 4.10 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from commercial unitary air-conditioning. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.10 – Technological Options for Commercial Unitary Air-conditioning

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Refrigerant recovery/recycling[1]	-	10	95	10	\$26.19	\$3.40	\$1.69
Leak repair[2]	5	5	90	0-4	\$27.55	\$0.00	\$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{\text{CO2-Eq.}}$
1: CEC (2005); 2: IEA (2003) & USEPA (2001)

4.1.2 – Technical Aerosols

Various HFCs, such as HFC-34a, HFC-152a, HFC-227ea, are used as propellants in aerosol applications. The emissions of high GWP gases, mainly HFCs, from technical aerosols account for ~10.7% of their emissions from the sector of ODS substitutes in the United States (USEPA, 2006a).

Out of the 11.1 MMT$_{\text{CO2-Eq.}}$ emissions in 2004, the end-uses that contribute most toward emissions of HFCs as technical aerosols in the United States include:

- Metered dose inhalers (MDIs) – The MDIs, critically important in treatment of asthma and chronic obstructive pulmonary disease, will account for one-third of all aerosol HFC-equivalent emissions by 2010 (USEPA, 2001).
- Consumer products – Formulated consumer products include hairsprays, mousse, deodorants and anti-perspirants, household products, spray paints, and automotive products. Many of these products use HFCs to comply with regulations that reduce allowable VOC content (USEPA, 2001).
- Specialty products – Specialty aerosol end-uses include tire inflators, electronics cleaning products, dust removal, freeze spray, signaling devices, and mold release agents. HFCs are often used when flammability issues cannot be overcome (USEPA, 2001).

Although hydrocarbons can be used as propellants in many commercial aerosols, they have not been found acceptable for use in MDIs (USEPA, 2004). Nitrogen is another alternative as the propellant (IEA, 2001). The main technological option for reducing HFCs from end-use of MDIs is dry powder inhalers (DPIs). DPIs have been successfully used with most anti-asthma drugs; however, they may not be applicable to all patients or all drugs (e.g., applicable only to patients who can inhale robustly enough to transport powders to their lungs). In addition, the powders may aggregate under hot and humid climates (March Consulting Group, 1999; UNEP, 2002). However, the use of DPIs in Europe is increasing, as an example DPIs account for 85% of inhaled medication (USEPA, 2001).

Table 4.11 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of the technological option for emission reduction from end-uses of MDIs. More detailed description and analyses of this technological option can be found in Appendix C.

Table 4.11 – Technological Options for End-uses of MDIs

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Dry powder inhalers[1]	15	5	100	50	$294.21	$0.00	0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

A trend is developing for novel oral treatment that would be swallowed, rather than inhaled. They may become available in the next 10 to 20 years, but they would not completely replace inhaled MDI therapy. It should be noted that MDIs are medical devices; substitute propellants need to meet stringent performance and toxicology specifications (USEPA, 2004).

There are several technological options for reducing HFCs emissions from the non-MDI aerosol end-uses, mainly as consumer products and specialty products:

- Substitution with lower GWP HFCs – HFC-134a is often the propellant of choice for products that must be non-flammable, e.g., dust-removing agent for electronic equipment and long reaching insecticide products used on high-voltage power lines and transformers (IEA, 2001). Replacement of HFC-134a with a lower GWP HFC, such as HFC-152a which posses only moderate flammability hazards, will greatly reduce emissions from the aerosol sectors (USEPA, 2004).
- Not-in-kind (NIK) alternatives – They include finger-trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. They often prove to be better and more cost-effective than HFC-propelled aerosols (USEPA, 2004).
- Hydrocarbon aerosol propellants – They are usually mixtures of propane, butane, and isobutane. Their costs are typically less than one-tenth that of HFCs. However, flammability and VOC emission are of major concern. Dimethyl ether is another flammable alternative for aerosol propellant (USEPA, 2001).
- Compressed gases – Noninflammable gases including CO_2, N_2, compressed air, or even nitrous oxide can be used in aerosol applications. However, the gradual decrease of propellant pressure as the aerosol can is emptied makes them less effective (March Consulting Group, 1998). Technologies have been advanced to offset the effects of decreasing pressure through innovative valve configuration and proper selection of compatible solvents (UNEP, 1998).

Table 4.12 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from end-uses of consumer products and specialty products. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.12 – Technological Options for End-uses of Consumer Products and Specialty Products

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Substitution with lower GWP HFCs[1]	10	25	91	48	\$0.75	-\$2.52	\$0.00
VOC propellants[1]	10	10	100	40	\$0.44	-\$5.60	\$0.00
Not-in-kind (NIK) products[1]	10	10	100	100	\$0.34	-\$5.26	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{\text{CO2-Eq.}}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

4.1.3 – Solvents

HFCs, especially HFC-4310mee, and PFCs are used as solvents for various industrial cleaning applications, including precision, electronics, and metal cleaning. HFC emissions from the precision and electronics cleaning end-uses currently dominate the GWP-weighted emissions from this sector (UNEP, 1999b; USEPA, 2004). The emissions of these GWP gases from solvent uses account for ~1.5% of their emissions from the sector of ODS substitutes in the United States (USEPA, 2006a).

There are several technological options for reducing HFC/PFC emissions from solvent uses:

- Improved equipment and cleaning processes using existing solvent – Better engineering control (e.g., increasing freeboard height, installing freeboard chillers, less drag-out losses, and using automatic hoists) and improved containment (e.g., better solvent bath enclosure and better vapor condensing systems) will minimize emissions and losses of existing solvents (March Consultiing Group, 1998 & 1999; UNEP, 1999b).
- Recycle and recovery – For cases where HFCs and PFCs continue to be used for performance reasons, the emission can be minimized from recycle and reuse. In many cases, the reduced costs of solvent disposal offset the purchase cost of solvent reclamation equipment (UNEP, 1999b). Post-combustion of exhaust air from the cleaning process can be used for destruction of the contained solvents (IEA, 2001).
- Not-in-kind (NIK) technologies – Aqueous and semi-aqueous NIK replacement options can displace HFC and PFC usage in some solvent applications. Aqueous cleaning uses a water-based cleaning solution that often contains detergents. The products are then rinsed with water. Although the material costs are lower, the energy cost is often higher and subsequent wastewater treatment or disposal is needed. The semi-aqueous cleaning process uses a solution consisting of hydrocarbon and surfactant to remove contaminants. The products are then rinsed with water. These processes have lower material and energy costs than traditional solvent processes. They have good cleaning ability, suppressed vapor pressure, and reduced evaporative loss; however, wastewater treatment or disposal is needed along with concerns of flammability and VOC emissions (UNEP, 1999b, USEPA, 2004).
- Alternative solvents – Alternative organic solvents with lower GWPs, such as hydrofluoroethers (HFEs), hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, non-ODS chlorinated solvents, are being used in electronics, metal, and some precision cleaning end-uses (USEPA, 2001). HFE solvents are gaining acceptance in the U.S. industry due to their availability, safety, and effectiveness (USEPA, 2004).

Table 4.13 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from solvent uses. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.13 – Technological Options for Solvent Uses

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Improved equipment and cleaning processes[1]	10	0	46 - 90	90 - 100	$370.37	$0.00	$27.84
Aqueous cleaning[1]	10	5	100	90 - 100	$40.00	$0.00	$0.00
Semi-aqueous cleaning[1]	10	3	100	90 - 100	$22.22	$0.00	$0.00
Alternative solvents[1]	10	30	85	5 - 100	$0.00	$1.29	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

4.1.4 – Foams

Foams are used for thermal and sound insulation as well as cushioning. Various HFCs, such as HFC-134a, HFC-152a, HFC-245fa, and HFC-365mfc, are used as the blowing agents during the manufacture of foams. These blowing agents might be emitted to the atmosphere during foam manufacturing or on-site foam application, while foams are in use, and when foams are disposed of. The foams can be categorized by the composition (e.g., polyurethane, polystyrene, or polyolefin), type of cell (open vs. closed), manufacturing process (spray vs. extrusion; thermoset vs. thermoplastic), and the properties (rigid vs. flexible).

Technological options to reduce HFC emissions from foams include the following (USEPA, 2001; USEPA 2004):

- Alternative blowing agents – Hydrocarbons (propane, butane, pentane, and hexane), water-blown CO_2, and liquid CO_2 are alternatives to HFCs as the blowing agents. Due to the flammability, stringent safety precautions and specialized equipment may be required. In addition, most of these hydrocarbons are part of the VOC family, emission control may be needed and it will increase the cost of conversion. Some of the hydrocarbons may not yield comparable insulating values of HFCs, and, consequently, a thicker form may be required. In the liquid carbon dioxide process, liquid CO_2 is blended with other foam constituents under pressure prior to the initiation of chemical reaction. Once the pressure is reduced, the expansion of CO_2 results in the froth foam. In the water-blown (in-situ) carbon dioxide process, CO_2 produced from a chemical reaction between water and polymeric isocyanate serves as the blowing agent. The quality of foam products from either CO_2 process may be improved by blending CO_2 with hydrocarbons or HFCs (William *et al.*, 1999; USEPA, 2004).
- Lower-GWP HFC substitution – HFC-134a is the HFC that is most-commonly used in the foam industry, but some other lower GWP HFCs, such as HFC-245fa, are viable alternatives. However, choices of blowing agents are usually driven by performance and economic considerations (USEPA, 2001).

- Alternative insulation materials and technologies – Alternative insulation technologies are available in some construction applications include fiberboard, fiberglass, and cellular glass. However, HFC foams, despite higher costs, are still used often because of superior properties in fire resistance, structural rigidity, moisture resistance, and insulation effectiveness (March Consulting Group, 1998). Vacuum panels have better insulating capability, but they are still too expensive. Reliable cost information for these options is not available in literature.
- Direct emission reduction – Various direct emission reduction measures can be adopted in production, usage, and decommissioning of the foams. Examples include vapor capture at the "head", use of low-permeability facing, recycle and recovery, and destruction by incineration (USEPA, 2001). It is difficult to generalize the cost information associated with these abatement options (March Consulting Group, 1998).

Table 4.14 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from the end-uses of foam. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.14 – Technological Options for Foam Sector

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Replace HFC-134a in appliance with hydrocarbons[1]	25	25	100	0-2	$105.79	-$3.19	$0.00
Replace HFC-245fa in appliance with hydrocarbons[1]	25	15	100	0-10	$144.40	$32.35	$0.00
Replace HFC-245fa in sprays with hydrocarbons[1]	25	10	100	0-26	$7.81	-$3.82	$0.00
Replace HFC-245fa in sprays with water-blown CO_2[1]	25	5	100	0-26	$2.23	$23.97	$0.00
Replace HFC-134a or 152a in extruded polystyrene with water-blown CO_2[1]	25	0	100	37-100	$8.89	-$0.14	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

4.1.5 – Fire Extinguishing

HFCs (HFC-227ea, HFC-236fa, HFC-23) and perfluromethane (CF_4) are the principal greenhouse gases emitted from the fire extinguishing systems. Basically there are two types of fire fighting systems: portable fire extinguishers and total flooding applications. Portable fire extinguishers are used widely; foam, water, CO_2, or dry powder is commonly used. Market penetration of HFCs and PFCs in this sector is very limited (USEPA, 2001). Sensitive systems such as computer and telecommunication servers are contained in sealed rooms and equipped with fixed extinguishing systems that flood the room in case of fire (total flooding systems). To ensure that people working in this environment is not harmed, non-toxic extinguishing agents are needed and HFCs and PFCs are more commonly used.

The technological options for reducing HFC and PFC emissions from the fire protection sector include the use of alternative fire protection agents and alternative technologies and practices (USEPA, 2001& 2004):

- Alternative fire protection agents – Carbon dioxide has been used in total flooding systems for many years; however, safety standards regulate its use in occupied areas because lethal concentrations of carbon dioxide are needed during fire fighting. Water mist and inert gases systems are alternatives to some HFC uses in total flooding systems (USEPA, 2001). The water mist option is more economic than the inert gas option, but it has a lower abatement potential because of its limited technical applicability (IEA, 2003)
- Alternative technologies and practices – Improved fire prevention technologies may reduce emissions of HFCs and PFCs. The viable options include early warning smoke detection, infrared cameras to distinguish real fires from false alarm, and technologies to reduce the amount of agent discharge to prevent a fire (USEPA, 2001).

Table 4.15 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from the fire-fighting sector. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.15 – Technological Options for Fire-Fighting Sector

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Water mist systems[1]	10	50	100	1-4	-$35.71	$0.00	$0.00
Inert gas systems[1]	10	20	100	15-76	$98.57	$3.57	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

4.1.6 – Sterilization

Sterilization is used to control microorganisms and pathogens during the growing, collecting, storing and distribution of various foods including grains, vegetable, and fruits. Many low temperature sterilization techniques utilize an ethylene oxide/CFC mixture. Currently the USEPA Vintaging Model assumes that this sector has not transitioned to any HFC or PFC uses as an ODS substitute (Godwin *et al.*, 2003). No technological options for reducing HFCs or PFCs from this sector were found from the literature search.

4.2 – Electrical Transmission and Distribution

Sulfur hexafluoride (SF_6) is a colorless, odorless, non-toxic, and nonflammable gas, but it has a GWP that is 22,200 times that of CO_2 for a 100-yr time horizon and a lifetime of 3,200 years in the atmosphere. It has been used by the electric power industry since the 1950s because of its dielectric strength and arc-quenching characteristics. The largest use of SF_6 in the United States is as an electrical insulator and interrupter in equipment that transmits and distributes electricity. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in populated urban areas (USEPA, 2006a).

Typical applications of SF_6 in high voltage technology include gas-insulated switchgear (GIS), circuit breakers, and gas insulated lines (GIL). SF_6 can escape from gas-insulated substations and switchgear through gasket seals, flanges, and threaded fittings, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, SF_6 analysis, and disposal. Emissions of SF_6 from electrical transmission and distribution were 13.8 $MMT_{CO2\text{-}Eq.}$ in 2004 in the United States. It represents a 52% decrease from 1990. Several plausible reasons for the decrease, including (1) increases of price of SF_6 during 1990s, (2) growing awareness of the environmental impact of SF_6 emissions, and (3) programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power System (USEPA, 2006a).

The high GWP gases emissions from electrical transmission and distribution in California were 1.02 $MMT_{CO2\text{-}Eq.}$ in 2004, 7.2% of the state's total high GWP gases emissions, 14.2 $MMT_{CO2\text{-}Eq.}$ (see Table 4.1).

The technological options for reducing SF_6 emissions from electric power transmission and distribution can be grouped into the following categories:

- Use of recycling equipment – Recycling equipment can capture and recycle SF_6 gas during equipment maintenance and retirement. It was estimated that recycling could reduce 10% of total SF_6 emissions from the electric power systems in the U.S. (USEPA, 2001). Recycling gas cart systems typically withdraw, purify, and return the SF_6 gas back to the gas-insulated equipment. The use of recycling equipment is a relatively straightforward option and has increased significantly worldwide (USEPA, 2006b).
- Leak detection and repair (LDAR) – This option aims to identify and reduce the SF_6 leakage from the gas-insulated equipment. The leak detection is accomplished through various techniques, including sniffing with SF_6 gas sensors and using a laser-based remote sensing technology (McRae, 2000). The laser leak detection system can accurately find leaks without any modifications or physical connection to circuit breakers; they have been successfully applied at many utilities (Moore, 1999). The capital cost of such a camera is approximately $100,000 (USEPA, 2001). It was estimated that the practice could reduce 20% of total SF_6 emissions from this sector in the U.S. (USEPA, 2004).
- Equipment replacement/refurbishment – Equipment replacement/refurbishment addresses the need, when the leakage losses are large and beyond the LDAR-based repairs (USEPA, 2006b). The older equipment of this sector tends to use larger amount of SF_6 and has higher leak rates than newer equipment. Generally the cheaper of two possible options will be chosen: (1) equipment replacement, which can be on the order of $300,000 to $400,000 for a larger 362 kV breaker; and (2) refurbishment, which may cost around $100,000 (McCracken *et al.*, 2000). Fifty percent or more of all emissions from older equipment could be avoided if the equipment were replaced by new "tighter" unit (USEPA, 2001).
- Others – Despite extensive research efforts, no single gaseous compound has been identified to serve as a substitute for SF_6 in high-voltage applications. However, gas mixtures, such as SF_6/N_2 or SF_6/CF_4, have been successfully used in cold-weather applications (US Climate Change, 2005). In addition, 145kV interrupters, developed by Japan AE Power, are commercially available in Japan; The Electric Power Research Institute (EPRI) is investigating a solid-state current limiter that may lead to future designs without SF_6 insulation requirement (US Climate Change, 2005).

Table 4.16 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from electric power transmission and distribution systems. It should be noted that the technological option of leakage reduction and recovery is a combination of leak detection, leak repair, and recycling which are well-developed technologies and are considered as a basic option for conservative gas handling practices (CEC, 2005). More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.16 – Technological Options for Electric Power Transmission and Distribution Systems

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leakage reduction and recovery[1]	10	100	100	100	$10.96	$1.81	$0.00
Improved SF_6 recovery for electric gas insulated switch gear manufacture[2]	15	-	100	30-60	$1.84	$0.01 – 0.6	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001) & CEC (2005); 2: IEA (2003)

4.3 – Semiconductor Manufacture

Several long-life fluorinated gases (CF_4, C_2F_6, C_3F_8, C_4F_8, HFC-23, NF_3, and SF_6) are currently used in the semiconductor industry. A fraction of these gases is emitted from two frequently used manufacturing processes to produce semi-conductor products: plasma etching of thin films and cleaning of plasma-enhanced chemical vapor deposition (PECVD) chambers. Chemical vapor deposition (CVD) chamber cleaning is estimated to account for 80% of the emissions from semiconductor manufacturing; while the etching process is estimated to account for 20% (USEPA, 2006b). For 2004, the total weighted emissions of all fluorinated greenhouse gases by the semiconductor manufacturers in the United States were 4.7 $MMT_{CO2\text{-}Eq.}$ The breakdown of the emissions is shown below (USEPA, 2006a):

Perfluoroethane (C_2F_6):	2.2 $MMT_{CO2\text{-}Eq.}$
Perfluoromethane (CF_4):	1.2 $MMT_{CO2\text{-}Eq.}$
Sulfur hexafluoride (SF_6):	0.9 $MMT_{CO2\text{-}Eq.}$
Nitrogen trifluoride (NF_3):	0.3 $MMT_{CO2\text{-}Eq.}$
Trifluoromethane (HFC-23):	0.2 $MMT_{CO2\text{-}Eq.}$
Perfluorocyclobutane (C_4F_8):	0.1 $MMT_{CO2\text{-}Eq.}$
Perfluoropropane (C_3F_8):	0.0 $MMT_{CO2\text{-}Eq.}$

The high-GWP gases emissions from semi-conductor manufacture in CA were 0.57 $MMT_{CO2\text{-}Eq.}$ in 2004, 4.0% of the state's total high GWP gases emissions, 14.2 $MMT_{CO2\text{-}Eq.}$ (see Table 4.1)

The technological options that can reduce HFCs, PFCs, and SF_6 from semiconductor manufacturing can be grouped into the following categories:

- NF_3 remote clean technology – Perfluoroethane (C_2H_6) has been the primary CVD chamber clean gas in the semiconductor manufacturing processes. Two basic NF_3 clean technologies are available as alternatives. The first technology introduces NF_3 directly into the CVD process chamber (in situ) where the gas is dissociated into plasma. The other dissociates NF_3 into plasma upstream of the CVD process chamber and the active N and F atoms are then delivered to the chamber to clean the deposited material (USEPA, 2001). The NF_3 remote clean system is assumed to be applicable to all fabrication facilities (USEPA, 2006b). AMAT and ASTeX have deployed remote cleaning processes; IBM and Novellus have commercialized and deployed dilute NF_3 cleaning processes (US Climate Change, 2005).

- C_3F_8 replacement – C_3F_8 has a smaller 100-yr global warming potential than C_2F_6 (7,000 vs. 9,200) and a much shorter atmospheric lifetime (2,600 vs. 10,000 years). In addition, C_3F_8 is more efficiently used or consumed during the CVD chamber cleaning process than C_2F_6. It is assumed that the C_3F_8 replacement would yield an emission reduction efficiency of 85%, and this option should be applicable to all fabrication facilities (USEPA, 2006b). C_3F_8 is reportedly used in commercial applications at AMD, Motorola, and Texas Instrument (US Climate Change, 2005).
- Point-of-use (POU) plasma abatement system – The system is to reduce emissions from the etching process and it should be applicable to all fabrication facilities (USEPA, 2006b). The POU plasma abatement system uses a small plasma source, and it can be located in the fore line of an etch tool or in the gas line between the process tool and the main pump (Motorola, 1999). The "Blue" system of Litmas Inc. uses an inductively coupled radio frequency plasma source, while the AMAT Pegasys^{TM} POU unit uses cold-plasma technology that makes the abatement unit transparent to process engineers (US Climate Change, 2005).
- Thermal destruction/thermal processing units (TPU) – This can be used to reduce PFC emissions from both the etching and the CVD chamber cleaning processes and should be applicable to all fabrication facilities (USEPA, 2006b). Thermal destruction units are installed after the semiconductor production units and, thus, they do not affect the manufacturing process. However the combustion devices use a significant amount of cooling water and produce NO_x emissions, which are regulated air pollutants (Applied Material, 1999). The Edwards TPU 4214 using oxidation with advanced burner technology can achieve more than 99% destruction efficiency and is the only thermal-destruction device in commercial uses (US Climate Change, 2005).
- Catalytic decomposition system – The catalytic systems are very similar to the thermal destruction units, but operate at lower temperatures because the presence of the catalyst. They produce little or no NO_x emissions and demand lower volumes of cooling water (Applied Materials, 1999). It was reported that the Hitachi system using catalytic oxidation technology can achieve more than 99% destruction efficiency for CF_4, C_2F_6, C_4F_8, and SF_6 (US Climate Change, 2005).
- Facility-wide solutions – These solutions include PFC capture/recovery and process optimization. The capture/recovery membrane can be used to reduce PFC emissions from both the etching and the CVD chamber cleaning processes and should be applicable to all fabrication facilities (USEPA, 2006b). The membrane separates un-reacted and/or process-generated PFCs from other gases for further processing. These capture/recovery systems can re-process the PFC for reuse or concentrate the gas for subsequent off-site disposal. However, the semiconductor process engineers often have little or no interest in reusing the gas for fear of possible process harming impurities (USEPA, 2006b). In addition to membrane separation, there are other recovery-and-recycle technologies reported in literature: Praxair/Ecoys cryogenic capture system and MEGASORB and BOC pressure swing system. The MEGASORB and BOC systems have shown low capture efficiencies. Although both cryogenic capture and membrane technologies have received encouraging press reports from chip manufacturers, there are no published reports of commercial uses (US Climate Change,

2005). Process optimization can also reduce emission; one example is to use end-point detectors and/or process parameter variation to determine the optimal fluorocarbon utilization to reduce excess emissions.

Table 4.17 summarizes the information that was found in literature regarding cost, market penetration (in 2010), emission reduction efficiency, and technical applicability (in 2010) of technological options for emission reduction from the semiconductor manufacture sector. More detailed description and analyses of these technological options can be found in Appendix C.

Table 4.17 – Technological Options for Semiconductor Sector

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
CVD cleaning emission reduction – NF_3 remote clean[1]	5	90	90	60	$90.76	$0.00	$0.00
CVD cleaning emission reduction – C_3F_8 replacement[2]	5	-	100	70-90	$0.00	$0.00	$0.00
Point-of-use plasma abatement[1]	5	55	97	10	$50.81	$1.45	$0.00
Thermal destruction or processing units[1]	5	20	90	40	$93.39	$8.98	$0.00
Catalytic decomposition system[1]	5	20	98	40	$67.35	$5.32	$0.00
PFC recapture/recovery[1]	5	8	90	100	$40.52	$13.20	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2\text{-}Eq.}$
1: CEC (2005) & USEPA (2001); 2: IEA (2003) & USEPA (2001)

References

A. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

Applied Materials (1999) "Catalytic Abatement of PFC Emissions", *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

Baker, J. (2000) "Vehicle Performance of Secondary Loop Air Conditioning Systems (Using Flammable Refrigerants)", *Proc. MACS 2000 Technical Conference*, Las Vegas, NV, January 2000.

Baker, J.A. (1998) "Mobile Air Conditioning and Global Warming". *Proc. Phoenix Alternate Refrigerant Forum 1998*, Suntest Engineering, Scottsdale, AZ.

BOC Gases Ltd. (2007) Information on Care Refrigerant Product (http://www.care-refrigerants.co.uk/hmpg/)

California Air Resources Board (2004) "Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles", California Air Resources Board, August 6, 2004.

California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.

Cooper, P.J. (1997) “Experience with Secondary Loop Refrigeration Systems in European Supermarkets”, *Proc. International Conference on Ozone Protection Technologies*, September 27-29, Washington, D.C.

Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.

Environment Canada (1998) “Powering GHG Reductions through Technology Advancement”, Clean Technology Advancement Division, Environment Canada.

Fisher, S.K.; Tomlinson, J.J.; Hughes, P.J. (1994) “Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-kind and Next Generation CFC and HCFC Alternatives”, prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.

Godwin, D.S.; Van Pelt, M.M.; Peterson, K. (2003) Modeling Emissions of High Global Warming Potential Gases, *Proc. USEPA 12th International Emission Inventory Conference – Emission Inventories: Applying New Technologies*, San Diego, April 29 – May 1.

International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

Intergovernmental Panel on Climate Change - IPCC (2000) “Climate Change 2000”, The Third Assessment Report - Working Group 3, Final Draft, October 2000.

Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.

Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

March Consulting Group (1998) “Opportunities to Minimise Emissions of HFCs from the European Union”, Commissioned by Directorate General Enterprise of the European Commission; United Kingdom, September 1998.

March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.

Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

McCracken, G.A.; Christiansen, R.; Turpin, M. (2000) “The Environmental Benefits of Remanufacturing: Beyond SF_6 Emission Reduction”, *Proc. International Conference on SF_6 and the Environment: Emission Reduction Strategies*, November 1-3, San Diego, CA.

McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.

McRae, T. (2000) “GasVue and the Magnesium Industry: Advanced SF_6 Leak Detection”, *Proc. International Conference on SF_6 and the Environment: Emission Reduction Strategies*, November 1-3, San Diego, CA.

Moore, T. (1999) “Seeing SF_6 in a New Light”, *EPRI Journal*, Summer 1999, Palo Alto, CA.

Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.

Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.

U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

U.S. Environmental Protection Agency (1998) “1998 Report of the Technology and Economic Assessment Panel (pursuant to Article 6 of the Montreal Protocol)”, U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.

U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.

U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006

U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.

UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.

UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.

UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.

Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Wertenbach, J.; Maue, J.; Volz, W. (1996) “CO_2 Refrigeration System in Automobile Air Conditioning”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

William, D.J.; Bogdan, M.C.; Logsdon, P.B. (1999) “Optimizing Performance and Value: HFC-245a and Blends of HFC-245fa for Insulating Foams”, *Proc. Earth Technologies Forum*, Washington, D.C., September 27-29.

CHAPTER 5

BLACK CARBON

5.0 - Introduction

Black carbon aerosols are particulates formed by incomplete combustion of carbon-containing fuels. They have been identified as having potentially significant impacts on climate change, especially at a regional scale. Black carbon particles have a relatively short atmospheric lifetime (days to weeks) and, therefore, they are not well-mixed in the atmosphere, unlike other greenhouse gases which are well-mixed due to their long atmospheric lifetimes in the range of decades to centuries. Black carbon is generally considered to have both a direct warming effect by absorbing the incoming solar irradiation in the atmosphere and an additional warming effect by reducing the albedo (reflectivity) of snow and ice (Bahner *et al.*, 2007).

Black carbon (BC) is usually co-emitted with organic carbon (OC) from combustion in various ratios depending on fuel type, combustion technology and efficiency, and the extent of emissions control. BC and OC are the main components of soot. Black carbon is the main light-absorbing component of soot. Black carbon can also be defined as carbonaceous light absorbing aerosol components that come into being from incomplete combustion. Although they are not exactly the same, black carbon is sometimes treated as equivalent to elemental carbon (EC). Some believe that control of fossil fuel soot (BC + OC) may be the fastest way of slowing warming for a specific period (Jacobson, 2004).

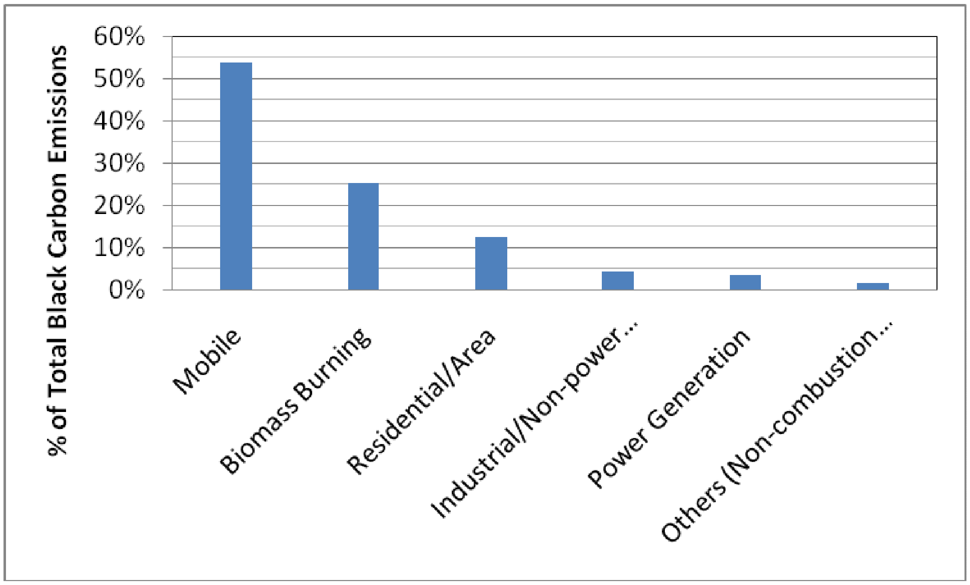
Black carbon emissions are seldom quantified, so data on the emission rates of black carbon are scarce in literature. Black carbon emission values are often derived from $PM_{2.5}$ estimates with some simplified assumptions (Somers, 2004). The reported emission data usually do not follow the six-sector approach that is commonly used for GHG emission inventories. Most of the literature categorizes the BC emissions into mobile sources and stationary sources, since combustion is the dominant source of BC emissions into the atmosphere.

US EPA developed inventories for BC as part of the National Ambient Air Quality Standards (NAAQS) Regulation Impact Analyses (USEPA, 2006; Bahner *et al.*, 2007); and the data are summarized in Table 5.1. As shown, the top contributors for BC emissions in the United States, in the order of magnitude, are mobile sources (53.5%), biomass burning (25.2%), residential/area sources (12.4%), industrial/non-power generating point sources (4.1%), power generation (3.2%), and non-combustion sources (1.6%). Combustion is the dominant source, 98.6%, of BC emissions, while non-combustion sources only account for 1.6%. Other estimates on BC emissions of the United States can be found in Battye *et al.* (2002), Streets *et al.* (2004), and Miller (2004). The percentage emissions of major sources in the USA are plotted, in a descending order, in Figures 5.1.

Table 5.1 – Estimates of Black Carbon Emissions in the USA in 2001

	USA (2001)	
Source	**Gg**	**(%)**
Biomass Burning	110	25.2%
Residential/Area	54	12.4%
Industrial/Non-electrical Generating Utilities	18	4.1%
Mobile	234	53.5%
Power Generation	14	3.2%
Others (Non-combustion Sources)	7	1.6%
Total	**437**	100%

Figure 5.1 – Major Sources of Black Carbon Emissions in the USA (2001)



No California state-wide BC emission inventory data were found from the literature search. Kleeman (2004) compared the $PM_{2.5}$ elemental carbon emissions from rural San Joaquin Valley (data from CARB) and urban Los Angeles (data from the South Coast Air Quality Management Districts). The estimated emission rate of $PM_{2.5}$ EC from San Joaquin Valley in January of 1996 is 8.21 tons/day, and the major contributors are farming diesel fuel combustion (36%), construction and demolition (18%), other waste burning (12%), residential wood combustion (11%), on-road vehicles (6%), and other mobile (5%). The emission rate of $PM_{2.5}$ EC from the South Coast Air Basin in September of 1996 is 7.31 tons/day, comparable to that from the San Joaquin Valley. However, the relative contributions from various sectors are different; they are light-duty industrial diesel equipment (45%), on-road vehicles (27%), industrial processes (8%), trains (6%), fuel combustion (4%), and paved road dust (4%).

Discussion on BC emission sources and technological options for emission reduction in this chapter is presented in the following two sections: mobile and stationary sources.

5.1 – Mobile Source

Mobile sources account for more than 50% of BC emissions in the United States (see Table 5.1). Emissions from mobile combustion are often grouped by transport mode (e.g., highway, air, rail), fuel type (e.g., gasoline, diesel fuel, jet fuel), and vehicle type (e.g., passenger cars, light-duty trucks). Road transport accounted for most of the mobile source fuel consumption and, consequently, the majority of mobile combustion emissions.

The on-road mobile sources for black carbon emissions can be further divided into the following (Miller, 2004; Somers, 2004):

- On-road gasoline (passenger cars, light-duty trucks, heavy-duty trucks, motorcycles)
- On-road diesel (passenger cars, light-duty trucks, heavy-duty vehicles)

The non-road mobile sources for black carbon emissions can be further divided into the following (Miller, 2004; Somers, 2004):

- Non-road diesel (construction, farm, train, boats)
- Non-road gasoline (lawn/garden, recreation marine)

Diesel engines result in more black carbon emissions than gasoline engines. The best gasoline vehicles in the United States emit less black carbon than the best diesel vehicle can, even with a particle trap (Jacobson, 2004). In the United States, on-road and non-road diesel vehicles are the largest sources of BC emissions (DeAngelo, 2006). One estimate on BC emissions from a light-duty diesel vehicle is 4 mg/mile from exhaust, 1 mg/mi from brakes, and 3 mg/mi from tire wear (Cradle, 2004). The U.S. EPA has regulated emissions of particulate matter (PM) from on-road mobile sources for many years. The PM emissions from properly operating gasoline automobiles have decreased from 300 mg/mile to 1 mg/mile from 1970 to 2004; while those from diesel vehicles have decreased from about 2,500 mg/mile to 20 mg/mile (Somers, 2004). For diesel, non-road emissions are larger than on-road since regulations on particulate matters from non-road diesel are more recent. For gasoline, the non-road emissions are important, but data are very limited (Somers, 2004).

Since mobile sources, especially those associate with diesel, are responsible for most of the BC emissions, most technological options for BC emission reduction found from the literature search are for diesel vehicles and engines. Basically, BC is removed in the process that is mainly aimed for removal of particulate matter. It is difficult to compare the costs of BC mitigation options with those of other GHG mitigation options without an appropriate CO_2-equivalent metric (DeAngelo, 2006).

To date, most of the diesel PM reduction efforts have been focused on either new engine replacements or retrofitting engines with post-combustion emission control (Lyons, 2003). Specific technological options to reduce BC emissions from mobile sources include:

- Diesel particle filters (DPFs) – DPFs, also known as “trap”, remove PM from the diesel exhaust through physical filtration. DPFs must be supplemented with means of self-cleaning (regeneration) to remove the collected carbon and organic particles. This is done by adding heat to the exhaust, raising temperature high enough to oxidize carbon to gaseous carbon dioxide. Nonetheless, all DPFs still require periodic maintenance to clean-out ash that accumulates from the non-organic carbon components of the engine oil (Clean Air Task Force, 2005).
- Catalyst-based DPFs – The added catalyst effectively lowers the temperature required for regeneration of the filters. The catalyst can be poisoned by sulfur; therefore, this type of

DPFs can only be used with diesel fuel of ultra low sulfur content (Clean Air Task Force, 2005).

- Diesel oxidation catalysts (DOCs) – DOCs use the same type of catalyst material as that in the catalyst-based DPFs, but applied to a flow-through monolith, without the physical filter (Clean Air Task Force, 2005; Lyons, 2003). This is mainly for reduction of OC-based particulate matter and their removal efficiencies for BC should be relatively low.
- Closed crankcase emissions filtration device – In many diesel engines, crankcase emissions are released from the engine through the "road draft tube" without passing through the exhaust system. A closed crankcase filtration device, by rerouting crankcase ventilation back to the engine, can be fitted to school buses and eliminate these emissions (Clean Air Task Force, 2005).
- Alternatives to diesel – Biodiesel is mono-alkyl ester oxygenated fuel made from vegetable (soybean or canola) or animal fats. It has been demonstrated that using biodiesel can reduce emissions of particulate matter (Clean Air Task Force, 2005; Lyons, 2003).
- Engine modifications – Particulates emissions can also be reduced through improvements to the basic engine such as turbo-charging, after-cooling, high-pressure fuel injection, retarding injection timing, and optimizing combustion chamber design (Lyons, 2003).
- Proper maintenance of diesel engines
- Reduce idling of diesel engines
- Replace gas lawn mowers with electrical mowers
- Reduce fuel consumption
- Reduce vehicle use

5.2 – Stationary Source

The stationary sources of black carbon emissions include the following (Miller, 2004; Somers, 2004):

- Open burning (wildfires, prescribed burning, agricultural field burning, land clearing, other waste burning)
- Residential combustion (wood burning, yard waste burning)
- Utility combustion
- Industrial combustion
- Commercial combustion
- Incineration
- Fugitive dust
- Livestock

Biomass burning accounts for approximately 25% of BC emissions in the United States (see Table 5.1). Biomass burning is a difficult source to control; however, from a global warming mitigation perspective, it may be less important because OC is more dominant in terms of emissions and negative forcing (DeAngelo, 2006). Most PM emission control measures on utility and non-electric generating utilities (non-EGU) point sources are add-on technologies. These technologies include fabric filters (bag houses), electric static precipitators (ESPs), and wet scrubbers (USEPA, 2006). Specific technological options to reduce BC emissions from stationary sources include the following:

- Mitigation measures for diesels – If diesel engines are used in the stationary sources, then the measures discussed in Section 5.1 may be applicable. For example, applying diesel particulate filters to diesel-fueled compression-ignition engines can achieve up to 90% reduction in fine particulate matter (USEPA, 2006). Other measures such as engine modification, alternative fuels, reducing idle time, and proper maintenance should also reduce BC emissions.
- PM control measures for area sources – Specific controls exist for stationary area sources, including catalytic oxidizers on conveyorized char-broilers at restaurants that can reduce PM emissions by 80% (USEPA, 2006). Another example is to replace older woodstoves with those in compliance with the New Source Performance Standard (NSPS) for residential wood combustion (USEPA, 2006).
- Apply the end-of pipe control on utility and non-energy generating utilities (non-EGU) point sources – Use ESPs, bag houses, or wet scrubbers for particulate removal. Upgrade the existing systems to better remove finer particles may be needed: one example is to add more collector plates in an ESP system to increase its removal efficiency (USEPA, 2006).
- Alternatives to open biomass burning – Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning (US Climate Change, 2005).

References

Bahner, M.A.; Weitz, K.A.; Zapata, A.; DeAngelo, B. (2007) "Use of Black Carbon and Organic Carbon Inventories for Projection and Mitigation Analysis", *Proc. 16th Annual International Emission Inventory Conf.*, Emission Inventories: Integration, Analysis, and Communications, Raleigh, May 14-17.

Battye, W.; Boyle, K.; Pace, T.G. (2002) "Methods for Improving Global Inventories of Black Carbon and Organic Carbon Particulates", Report No. 68-D-98-046 prepared for U.S. Environmental Protection Agency.

Clean Air Task Force (2005) "Diesel Engines: Emissions Controls and Retrofits", www.catf.us, v.3, revised 4-2005.

Cradle, S.H. (2004) "On-road Mobile Source PM and Black Carbon Emission Rates", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop,* U.S. Environmental Protection Agency, San Diego, October 13-15.

DeAngelo, B.J. (2006) "Update of the EMF-22 Black Carbon", *Proc. EMF 22 Climate Policy Scenarios for Stabilization and in Transition,* Tsukuba, Japan, December 12-14.

Jacobson, M.Z. (2004) "Global Warming Impact of Black Carbon", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop,* U.S. Environmental Protection Agency, San Diego, October 13-15.

Kleeman, M.J. (2004) "Emissions of Black Carbon in California", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop,* U.S. Environmental Protection Agency, San Diego, October 13-15.

Lyons, K. (2003) "Assessment of Potential Strategies to Reduce Emissions from Diesel Engines in Washington State", a report prepared for Department of Ecology, State of Washington, Publication number 05-02-005.

Miller, C.A. (2004) "Carbon Emissions from Stationary Sources", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.

Somers, J. (2004) "Mobile Source Black Carbon Emissions", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.

Streets, D.G.; Bond, T.C.; Lee, T.; Jang, C. (2004) "On the Future of Carbonaceous Aerosol Emissions", *J. Geophys. Res.* Vol. 109, D24212.

U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

U.S. Environmental Protection Agency (2006) "Regulatory Impact Analyses - 2006 National Ambient Air Quality Standards for Particle Pollution", United States Environmental Protection Agency, October 6, 2006.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The non-CO_2 greenhouse gases (NCGGs) emissions in California were 75 $MMT_{CO2\text{-}Eq.}$ in 2004, approximately 18% of the total GHG emissions; out of this 18%, 7.6% came from nitrous oxide, 6.4% from methane, and 3.2% from HFCs, PFCs, and SF_6. To meet the California GHG targets set in the Executive Order S-3-05, emission reductions from NCGGs are critical.

The project started with a literature search to identify sources of NCGG emissions from various sectors in California. After the emission sources were identified, another comprehensive literature search was conducted to identify available technological options for NCGG emission reductions. A study was then conducted on gathered information to evaluate identified technological options for their applicability in California. Data and information regarding reduction efficiency, market penetration, technical availability, service lifetime, and costs on many viable technological options were then gathered, evaluated, and presented in a systematic way for easy comparison and use.

The top contributors for CH_4 emissions in California, in the order of magnitude are landfills (30.2%), enteric fermentation (25.9%), manure management (21.6%), wastewater treatment (6.1%), natural gas systems (5.0%), stationary combustion, (4.7%), mobile combustion (2.2%), rice cultivation (2.2%), petroleum system (1.8%), and field burning of agricultural residues (0.4%). Many viable technological options for emission reductions for these sectors, especially in oil and natural gas systems, landfills, manure management, enteric fermentation, and wastewater treatment were identified and described in Chapter 2 of this report.

The contributors for N_2O emissions in California, in the order of magnitude, are agricultural soil management (57.5%), mobile combustion (35.3%), human sewage (3.2%), manure management (2.7%), stationary combustion (0.6%), nitric acid production (0.5%), field burning of agricultural residues (0.2%), and municipal solid waste combustion (0.1%). Many viable technological options for emission reductions for these sectors, especially in agricultural soil management, manure management, mobile and stationary combustion, nitric acid production, and wastewater treatment were identified and described in Chapter 3 of this report.

Substitution of ODS with HFCs and PFCs is the dominant emission source of high-GWP gases in California and it represents 88.8% of total high-GWP gases emissions. Electrical transmission and distribution (7.2%) and semiconductor manufacture (4.0%) are the other two significant emission sources of high-GWP gases in California. Many viable technological options for emission reductions for all these three sectors were identified and described in Chapter 4 of the report.

No statewide black carbon emission inventories were found from the literature search. However, potential sources of black carbon emissions were described and technological options for emission reductions were presented in the report.

The findings of this project can serve as the basis for a web site to disseminate and act as a clearinghouse for non-CO_2 greenhouse gas control technology information. However, it should be noted that a periodic update of the database is needed because the identified technologies may be improved and additional technologies may become available in the future.

APPENDIX A

Technological Options for Emission Reduction of Methane

1. Energy Sector
    - 1.1 - Petroleum Systems
        - 1.1.1 - Production field operations
            - 1.1.1.1 - Flaring instead of venting
            - 1.1.1.2 - Associated gas (vented) mix with other options
            - 1.1.1.3 - Associated gas (flared) mix with other options
            - 1.1.1.4 - Option for flared gas (improved flaring efficiencies)
        - 1.1.2 - Crude oil transportation and refining operations (see Section 1.2.3)
    - 1.2 - Natural Gas Systems
        - 1.2.1 - Field production
            - 1.2.1.1 - Options to reduce emissions during well testing and completion
            - 1.2.1.2 - Installation of plunger-lift systems in gas wells
            - 1.2.1.3 - Use surge vessels for station/well venting
            - 1.2.1.4 - Replace high-bleed pneumatic devices with low-bleed pneumatic devices
            - 1.2.1.5 - Replace high-bleed pneumatic devices with compressed-air systems
            - 1.2.1.6 - Reducing the glycol circulation rates in dehydrators
            - 1.2.1.7 - Installation of flash tank separators on dehydrators
            - 1.2.1.8 - Other options for methane reductions related to dehydration
            - 1.2.1.9 - Redesign blow-down systems and alter emergency shutdown practices
            - 1.2.1.10 - Portable evacuation compressor for pipeline venting
            - 1.2.1.11 - Installation of electric starters on compressors
            - 1.2.1.12 - Replace gas starters with air
            - 1.2.1.13 - Replace gas starters with nitrogen
            - 1.2.1.14 - Replace ignition/reduce false starts
            - 1.2.1.15 - Automated air/fuel ratio controls
            - 1.2.1.16 - Reduce the frequency of engine starts with gas
            - 1.2.1.17 - Inspection and maintenance (pipeline leaks)
            - 1.2.1.18 - Inspection and maintenance (equipment and facilities)
            - 1.2.1.19 - Inspection and maintenance (chemical inspection pumps)
            - 1.2.1.20 - Inspection and maintenance (enhanced)
        - 1.2.2 - Processing (see Section 1.2.3)
        - 1.2.3 - Transmission and storage
            - 1.2.3.1 - Use surge vessels for station/well venting
            - 1.2.3.2 - Replace high-bleed pneumatic devices with low-bleed pneumatic devices
            - 1.2.3.3 - Replace high-bleed pneumatic devices with compressed-air systems
            - 1.2.3.4 - Reducing the glycol circulation rates in dehydrators
            - 1.2.3.5 - Installation of flash tank separators on dehydrators
            - 1.2.3.6 - Other options for methane reductions related to dehydration
            - 1.2.3.7 - Redesign blow-down systems and alter emergency shutdown practices
            - 1.2.3.8 - Portable evacuation compressor for pipeline venting
            - 1.2.3.9 - Installation of electric starters on compressors
            - 1.2.3.10 - Replace gas starters with air
            - 1.2.3.11 - Replace gas starters with nitrogen
            - 1.2.3.12 - Replace ignition/reduce false starts
            - 1.2.3.13 - Automated air/fuel ratio controls

        - 1.2.3.14 - Reduce the frequency of engine starts with gas
        - 1.2.3.15 - Replacement of reciprocating engines by gas turbines
        - 1.2.3.16 - Reciprocating compressor rod packing (Static-Pac)
        - 1.2.3.17 - Replace wet seals with dry seals on centrifugal compressors
        - 1.2.3.18 - Alter start-up procedure during maintenance (compressors)
        - 1.2.3.19 - Catalytic converter
        - 1.2.3.20 - Automate systems operation to reduce venting
        - 1.2.3.21 - Replace compressor cylinder unloaders
        - 1.2.3.22 - Other options for methane reductions related to compressors
        - 1.2.3.23 - Inspection and maintenance (pipeline leaks in transmission)
        - 1.2.3.24 - Inspection and maintenance (compressor stations)
        - 1.2.3.25 - Inspection and maintenance (compressor stations - enhanced)
        - 1.2.3.26 - Inspection and maintenance (storage wells)
        - 1.2.3.27 - Inspection and maintenance (storage wells - enhanced)
    - 1.2.4 - Distribution
        - 1.2.4.1 - Electronic monitoring at large surface facilities
        - 1.2.4.2 - Replacement of cast-iron/unprotected steel pipeline
        - 1.2.4.3 - Replacement of unprotected steel services
        - 1.2.4.4 - Inspection and maintenance (pipeline leaks)
        - 1.2.4.5 - Inspection and maintenance (enhanced)
- 1.3 - Stationary Combustion
- 1.4 - Mobile Combustion
- 1.5 - Abandoned Underground Coal Mines

2. Industrial Processes
3. Agriculture
    - 3.1 Enteric Fermentation
        - 3.1.1 - Improvements to animal husbandry/livestock reduction
        - 3.1.2 - Improved feed conversion efficiency
        - 3.1.3 - Improving animal productivity through the use of growth hormones
        - 3.1.4 - Improving genetic characteristics
        - 3.1.5 - Improving nutrition through strategic supplementation
        - 3.1.6 - Improving reproduction
        - 3.1.7 - Intensive grazing
    - 3.2 Manure Management
        - 3.2.1 - Anaerobic digestion systems
        - 3.2.2 - Aerobic digestion
    - 3.3 Rice Cultivation
        - 3.3.1 - Water management
        - 3.3.2 - Other options for methane reductions (excluding water management)
    - 3.4 Field Burning of Agriculture Residues
4. Land-use Change and Forestry
5. Wastes
    - 5.1 Landfills
        - 5.1.1 - Landfill gas recovery and utilization (direct gas use/upgrade to natural gas)
        - 5.1.2 - Landfill gas recovery and utilization (electricity generation)
        - 5.1.3 - Anaerobic digestion
        - 5.1.4 - Composting
        - 5.1.5 - Mechanical biological treatment
        - 5.1.6 - Increased oxidation
        - 5.1.7 - Other options for methane reductions related to landfills
    - 5.2 Wastewater Treatment

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Petroleum Systems (Production Field Operations)

Technology: Flaring instead of venting (A.1.1.1.1)

Description of the Technology:
Petroleum production field operations account for the majority, approximately 97%, of CH_4 emissions from the petroleum systems (USEPA, 2006a). The measures to reduce methane emissions from the petroleum systems can be grouped into prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

With regards to CH_4 emission reduction, flaring is a better alternative to venting because it destroys the gas rather than releasing it into the atmosphere and flaring converts methane to carbon dioxide which has a much lower GWP (USEPA, 2004; Hendriks & de Jager, 2001).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It destroys the gas rather than releasing it into the atmosphere and flaring converts methane to carbon dioxide which has a much lower GWP.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Flaring instead of venting[1]	15	100	98	5	$33.30	$1.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & IEA (2003)

Industry Acceptance Level: Widely accepted

Limitations: A good process control and monitoring system is needed to ensure that the flame is on.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
3. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Redction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

4. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
5. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
6. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
7. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Petroleum Systems (Production Field Operations)

Technology: Associated gas (vented) mix with other options (A.1.1.1.2)

Description of the Technology:
Petroleum production field operations account for the majority, approximately 97%, of CH_4 emissions from the petroleum systems (USEPA, 2006a). The measures to reduce methane emissions from the petroleum systems can be grouped into prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Instead of venting, emissions can be reduced by using the associated gas for consumption on the platform, and/or using the gas for domestic consumption by converting it to liquefied natural gas or to electricity (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It recycles and reduces the associated gas and reduces methane emission.

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Associated gas (vented) mix with other options[1]	15	100	90	23-25	\$69.54	\$1.11	\$3.71

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & IEA (2003)

Industry Acceptance Level: Widely accepted

Limitations: Additional investment on equipment is needed.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
3. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Redction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

4. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
5. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
6. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
7. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Petroleum Systems (Production Field Operations)

Technology: Associated gas (flared) mix with other options (A.1.1.1.3)

Description of the Technology:
Petroleum production field operations account for the majority, approximately 97%, of CH_4 emissions from the petroleum systems (USEPA, 2006a). The measures to reduce methane emissions from the petroleum systems can be grouped into prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Instead of venting or flaring, emissions can be reduced by using the associated gas for re-injection into the field for enhanced oil recovery, or for consumption within the facility.

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It recycles and reduces the associated gas and reduces methane emission.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Associated gas (flared) mix with other options[1]	15	100	95	14-15	$66.61	$2.21	$3.71

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$

1: USEPA (2004) & IEA (2003)

Industry Acceptance Level: Widely accepted

Limitations: Additional investment on equipment is needed.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
3. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Redction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

4. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
5. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
6. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
7. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Petroleum Systems (Production Field Operations)

Technology: Option for flared gas - improved flaring efficiencies (A.1.1.1.4)

Description of the Technology:
Petroleum production field operations account for the majority, approximately 97%, of CH_4 emissions from the petroleum systems (USEPA, 2006a). The measures to reduce methane emissions from the petroleum systems can be grouped into prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Based on information reported by CARB (2005), flare use is responsible for approximately 13% of CH_4 emissions from the petroleum sector in California. Implementation of techniques, such as optimization of flare burner pressure drop and exit velocities, could enhance the overall efficiencies of flaring from 90 to 99%, an additional 10% oxidation of CH_4 fed to the flare (CEC, 2005).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It destroys the gas rather than releasing it into the atmosphere and flaring converts methane to carbon dioxide which has a much lower GWP.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Option for flared gas (improved flaring efficiencies)[1]	15	100	10	13	$66.61	$2.21	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & EC (2001)

Industry Acceptance Level: Widely accepted

Limitations: Additional investment on equipment is needed.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.

3. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Redction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
4. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
5. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
6. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
7. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production)

Technology: Options to reduce emissions during well testing and completion (A.1.2.1.1)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Technological options to reduce CH_4 emissions from natural gas field operations during well testing and completion include the following:

- Good housekeeping practices to reduce blowouts – Improved equipment, procedures, and training of personnel would reduce the risks of blowout during exploration (de Jager *et al.*, 2001).
- Good operational procedures with regards to well-testing – Operational procedures can be optimized to minimize gas flow and duration of the tests during exploration. In the Netherlands, procedures have been tightened and the duration of a test is limited to 20 to 70 hours (de Jager *et al.*, 2001).
- Flaring of gas produced at well tests (during exploration) – Mobile flare installations can be used for this purpose to reduce methane emissions (de Jager *et al.*, 2001).
- Green completion – The common practice in gas well completion is to flare or vent initial produced gas. An alternative is to bring potable equipment to the well site that cleans up the initial produced gas to pipeline sales standard (Fernandez *et al.*, 2005).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions by minimizing venting and/or converting methane to carbon dioxide which has a much lower GWP.

Cost Effectiveness: Good

Industry Acceptance Level: Good

Limitations: Additional investment on equipment may be needed.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production)

Technology: Installation of plunger-lift systems in gas wells (A.1.2.1.2)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Venting is one of the traditional remedial operations for well blockage due to fluid accumulation. A plunger lift uses the natural energy of the well itself to lift the fluids out of the well to prevent well blockage. It will help maintain the production level and reduce methane emissions resulted from venting (USEPA, 2004; IEA 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Installation of plunger lift systems in gas wells[1]	10	100	4	1	\$3,986	\$159.42	\$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Capital and O&M costs are high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production; Processing; Transmission)

Technology: Use surge vessels for station/well venting (A.1.2.1.3; A.1.2.3.1)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

During production, processing, and distribution, a surge vessel can be used to enable gas emitted during blow-downs to be recaptured for reuse as fuel or re-injection into the pipeline (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Surge vessels for station/well venting[1]	10	100	50	<1	$11,216	$224.52	$8.53

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Capital and O&M costs are high.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production; Processing; Transmission)

Technology: Replace high-bleed pneumatic devices with low-bleed pneumatic devices (A.1.2.1.4; A.1.2.3.2)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

During production, processing, and distribution, high-bleed pneumatic devices (powered by natural gas) will emit a high volume of CH_4 to the atmosphere (USEPA, 2004; IEA, 2003). Field experience shows that up to 80% of all high-bleed devices can be replaced with low-bleed devices that emit much lower volumes of CH_4 (Tingley & Fernandez, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Replace high-bleed with low-bleed pneumatic devices[1]	5	50	86	8	\$14.01	\$0.00	\$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Only applicable to high-bleed pneumatic devices.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production; Processing; Transmission)

Technology: Replace high-bleed pneumatic devices with compressed-air systems (A.1.2.1.5; A.1.2.3.3)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Replacing of the high-bleed pneumatic devices (powered by natural gas) with compressed air systems will completely eliminate CH_4 emissions from these pneumatic devices in the natural gas production, processing, and distribution (USEPA, 2004; IEA, 2003). This is applicable at facilities with available electric power (Tingley & Fernandez, 2003). It should be noted that this option will incur some electricity-generation GHG emission.

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace high-bleed pneumatic devices with compressed air systems[1]	5	50	100	8	\$6.82	\$62.06	\$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Only applicable to high-bleed pneumatic devices.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production; Processing; Transmission)

Technology: Reducing the glycol circulation rates in dehydrators (A.1.2.1.6; A.1.2.3.4)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Tri-ethylene glycol (TEG) is circulated through dehydrators to absorb and remove water from the gas stream before the gas enters the transmission pipeline. TEG also absorbs some CH_4 that is vented. Reducing the TEG circulation rate to an optimal level will reduce CH_4 emissions (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Reducing glycol circulation rates in dehydrators[1]	1	50	31	1	$0.00	$1.72	$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$

1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Not applicable to Kimray pumps.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production; Processing; Transmission)

Technology: Installation of flash tank separators on dehydrators (A.1.2.1.7; A.1.2.3.5)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

A flash tank separator is used, by reducing the pressure of methane-rich tri-ethylene glycol (TEG) suddenly to cause the absorbed methane to flash (vaporize). The flashed methane can be collected and used as fuel gas or compressed and returned to the sales line (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Installation of flash tank separators[1]	5	50	54	3	$100.98	$0.00	$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Capital cost is relatively.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Field Production)

Technology: Other options for methane reductions related to dehydration (A.1.2.1.8; A.1.2.3.6)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

In addition to reducing glycol recirculation rate and installation of flash tank separators, there are other options for reducing methane emissions: they include:

- Replace glycol dehydrators with desiccant dehydrators (Tingley & Fernandez, 2003)
- Minimizing strip gas in glycol dehydration (Hendriks & de Jager, 2001)
- Increasing the pressure of the condensate flash (Hendriks & de Jager, 2001)
- Reroute glycol dehydrator vapor to vapor-recovery unit (Fernandez *et al.*, 2005)

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Data are not available.

Industry Acceptance Level: Good

Limitations: None reported

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Redesign blow-down systems and alter emergency shutdown practices (A.1.2.1.9; A.1.2.3.7)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

When a system is depressurized, emissions can result from “blow-down” (i.e., venting of the high-pressure gas left within the system). This option allows methane that would be vented when compressors are taken off-line to be re-routed to the fuel gas system (USEPA, 2004a; IEA, 2003). Relocating valves closer to the compressor can reduce the volume of gas release during depressurizing at changeover or routine maintenance (Hendriks & de Jager, 2001). Modifying the emergency shutdown (ESD) vents and blow-down piping enables collection and rerouting of the gas to the sales line, the fuel box, lower pressure mains for non-emergency use, or flare systems (USEPA, 2008).

Effectiveness: Emissions savings vary by compressor stations size, operating pressure, and facility complexity. Partners of the Gas STAR program reported annual emissions reductions ranging from less than 100 Mcf per year to more than 72,000 Mcf per year (USEPA, 2008).

For one partner of the Gas STAR program, installation of a blowdown recovery system at 7 compressor stations recovered 1,155 Mcf of gas that would have otherwise been vented to the atmosphere. An additional 1,275 Mcf savings was obtained by piping connections that lowered atmospheric venting pressure to approximately 60 psi (USEPA, 2008).

Implementability: This practice applies to all compressor stations.

Reliability: Good

Maturity: Good

Environmental Benefits: Methane emission reduction; Rerouting combustible gases eliminates potential hazards in the operating area as well as reducing methane emissions (USEPA, 2008).

Cost Effectiveness:
One partner of the Gas STAR program reported methane emissions reductions of 347 Mcf per year at one compressor station. This practice can provide payback in less than three years. Gas savings from rerouting blowdown systems to a sales line or for local fuel use should justify the piping and operating costs (USEPA, 2008).

- Capital Costs (including installation) : <$1,000
- Operating and Maintenance Costs (annual) : <$100

- Payback (Years): 1-3

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Fuel gas retrofit for blow-down valve[1]	5	100	33	21	$1.94	$0.00	$8.47

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Redesign of blow-down systems and altering ESD practices should be done in accordance with acceptable industry safety standards (OSHA, API, ANSI, ASME, and PSM).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
6. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
7. U.S. Environmental Protection Agency (2004a) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
8. U.S. Environmental Protection Agency (2004b) "Convert Engine Starting to Nitrogen", PRO Fact Sheet No. 101,http://www.epa.gov/gasstar/pdf/pro_pdfs_eng/convertenginestartingtonitrogen.pdf, Natural Gas Star Program, U.S. EPA, Washington DC, 2004.
9. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Portable evacuation compressor for pipeline venting (A.1.2.1.10; A.1.2.3.8)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

This option uses pump-down techniques to lower the pressure in the gas-line before venting in the natural gas production sector. An in-line portable compressor can be used to lower the line pressure by up to 90% of its original value without venting (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Portable evacuation compressor for pipeline venting[1]	15	100	72	<1	$318.58	$2.28	$8.52

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Need to have a portable evacuation compressor.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Installation of electric starters on compressors (A.1.2.1.11; A.1.2.3.9)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions (USEPA, 2004a; IEA, 2003). Partners of the Natural Gas Star Program have found that replacing the starter expansion turbine with an electric motor starter, similar to an automobile engine starter, can avoid methane emissions. The technology may include a connection to utility electrical power, site generated power, or solar recharged batteries (USEPA, 2008).

Effectiveness: Good

Implementability: This technology is applicable in all sectors of the gas industry.

Reliability: Good

Maturity: Good

Environmental Benefits: Conversion to electric starters completely eliminates the venting and the leakage of methane through the gas shutoff valve. Partners have reported savings of 23 Mcf to 600 Mcf per year, a range that is dependent on how many times compressors are restarted in a year and how readily the engine starts up and stays running. A single startup of a properly tuned engine may require 1 Mcf to 5 Mcf of gas at 200 psig average volume tank pressure, depending on engine size (horsepower). Blowdown valves of a size and pressure differential similar to the gas shutoff valve leak up to 150 scf per hour or 1.3 MMcf per year (USEPA, 2008).

Cost Effectiveness: Methane emissions savings of 1,350 Mcf per year apply to one engine starter, ten startups per year and methane leakage through the gas shutoff valve. This technology can provide a payback in less than three years. Important economic considerations include the capital cost of installing an electric starter motor, the revenue gained from salvaging the gas expansion turbine starter, and the cost of the electric power needed to drive the motor. The electrical energy required for the new starter will be equivalent to the energy imparted by the gas expansion. Using an electrical power cost of 7.5¢ per kWh, the gas expansion turbine above is equivalent to $1 to $5 per engine start attempt, depending on engine size (horsepower) (USEPA, 2008).

- Capital Costs (including installation): $1,000 - $10,000
- Operating and Maintenance Costs (annual) : <$100
- Payback (Years): 1-3

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Installation of electric starters on compressors[1]	10	-	75	<0.5	$838.62	$2,096	$6.82

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{\text{CO2-Eq.}}$

1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Electric starters require a power supply. Power can be provided from electrical utility, portable and solar-recharged batteries, or generated onsite (USEPA, 2008).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO$_2$ Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO$_2$ Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
5. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
6. U.S. Environmental Protection Agency (2004a) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
7. U.S. Environmental Protection Agency (2004b) "Convert Engine Starting to Nitrogen", PRO Fact Sheet No. 101,http://www.epa.gov/gasstar/pdf/pro_pdfs_eng/convertenginestartingtonitrogen.pdf, Natural Gas Star Program, U.S. EPA, Washington DC, 2004.
8. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission and Distribution)

Technology: Replace gas starters with air (A.1.2.1.12; A.1.2.3.10)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions. Replacing natural gas with air will completely eliminate the venting of methane (Fernandez *et al.*, 2005). Partners of the Natural Gas Star Program have found that replacing the natural gas with compressed air for engine starting can reduce methane, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) emissions.

Effectiveness: A methane emissions saving of 500 Mcf per year for multiple applications were reported (USEPA, 2008).

Implementability: This practice is applicable for all natural gas pneumatic starter motors.

Reliability: Reported methane emissions savings of 1,356 Mcf per year apply to one 3,000-horsepower reciprocating compressor that requires 10 startups per year. The compressor starter open-ended line is assumed to have average leakage (USEPA, 2008).

Maturity: Good

Environmental Benefits: Methane emissions reduction

Cost Effectiveness: The capital cost is the installation of piping between an existing air compressor and the starter is assumed to be incremental to the cost of the air compressor already used for pneumatic controls. Operating cost includes the electrical power needed to compress the air. Associated benefits include reduced VOC and HAP emissions (USEPA, 2008).

- Capital Costs (including installation): <$1,000
- Operating and Maintenance Costs (annual): $100 - $1,000
- Payback (Years): 0-1

Industry Acceptance Level: Fair

Limitations: A stationary or mobile air compressor is required for this practice.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2

Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004a) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2004b) "Convert Engine Starting to Nitrogen", PRO Fact Sheet No. 101,http://www.epa.gov/gasstar/pdf/pro_pdfs_eng/convertenginestartingtonitrogen.pdf, Natural Gas Star Program, U.S. EPA, Washington DC, 2004.
10. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Replace gas starters with nitrogen (A.1.2.1.13; A.1.2.3.11)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Small gas expansion turbine motors are often used to start internal combustion engines for compressors, generators, and pumps in natural gas production. These starters use compressed natural gas to provide the initial push to start the engine, but use of them results in methane emissions. Replacing natural gas with nitrogen will completely eliminate the venting of methane (USEPA, 2004a). Conversion to nitrogen completely eliminates the venting of methane to the atmosphere and the leakage of methane through the gas shut-off valve. Typical production site compressor engine startups vent 1 to 5 Mcf of gas with each attempt, while field engines often require multiple attempts. Blowdown valves of a size and pressure differential similar to the gas shut-off valve leak up to 150 scf per hour or 1.3 MMcf per year (USEPA, 2004a).

Effectiveness: Good

Implementability: Applicable to all compressors with gas pneumatic starter motors.

Reliability: Methane emissions reductions of 1,350 Mcf per year apply to converting one startup volume tank to nitrogen supporting ten engine starts per year. The volume tank is filled prior to startup to avoid leakage losses of nitrogen (USEPA, 2004a).

Maturity: Good

Environmental Benefits: Methane emission reductions

Cost Effectiveness: This practice can pay back quickly. The cost of compressed pipeline quality nitrogen is about $5 per Mcf delivered within 50 miles from commercial supply. For compressed nitrogen supply coinciding with startups, the value of avoided natural gas loss from leakage and startup vents may offset nitrogen costs. An associated benefit is reduced gas starter corrosion and maintenance costs when replacing the use of sour gas with nitrogen (USEPA, 2004a).

- Capital Costs (including installation) : <$1,000
- Operating and Maintenance Costs (annual): $100-$1,000
- Payback (Years): 0-1

Industry Acceptance Level: Enron Corporation and Marathon Oil Company work as a partner for this option (USEPA, 2008).

Limitations: Either the high-pressure startup gas system must be very tight (no leakage) or nitrogen re-supply made just prior to startups to ensure an adequate volume of high-pressure nitrogen. Re-supply of compressed nitrogen must be arranged on a schedule coinciding with engine startup frequency (USEPA, 2008).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004a) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2004b) "Convert Engine Starting to Nitrogen", PRO Fact Sheet No. 101,http://www.epa.gov/gasstar/pdf/pro_pdfs_eng/convertenginestartingtonitrogen.pdf, Natural Gas Star Program, U.S. EPA, Washington DC, 2004.
10. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Replace ignition/reduce false starts (A.1.2.1.14; A.1.2.3.12)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Before starting a compressor, the discharge header is unloaded by venting gas to the atmosphere. The engine is then turned over, often using a gas-expansion turbine starter. Both operations vent methane to atmosphere. Replacing old point-contact ignition systems with newer electronic designs can reduce false starts and eliminate methane emissions (Fernandez *et al.*, 2005).

Effectiveness: One partner of the Natural Gas Star Program reported reducing false starts from 150 to 10 per unit by replacing the ignition system, and saving 1,150 scf of methane per start (USEPA, 2008).

Implementability: This option may be applied to all engine driven compressors, pumps, and generators with outdated ignition systems (USEPA 2008).

Reliability: Methane emissions reductions of 21 Mcf per year result from replacing the ignition system on one 3,000-hp internal combustion engine and reducing startup attempts from 15 to 1 per year (USEPA, 2008).

Maturity: Good

Environmental Benefits: Methane emission reduction

Cost Effectiveness: This technology can pay back quickly. The primary justification is a reduction in operating costs. A unit with more than 100 false starts per year is an inconvenience to a company, as personnel must spend an inordinate amount of time attending to the unit. The value of natural gas savings coupled with significant labor savings will pay back the cost of upgrading ignition systems (USEPA, 2008).

- Capital Costs (including installation): $1,000-$10,000
- Operating and Maintenance Costs (annual): <$100
- Payback (Years): 0-1

Industry Acceptance Level: Southern California Gas Company

Limitations: Electronic ignition systems require a small amount of electricity, such as can be provided by a solar recharged battery (USEPA, 2008).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004a) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2004b) "Convert Engine Starting to Nitrogen", PRO Fact Sheet No. 101,http://www.epa.gov/gasstar/pdf/pro_pdfs_eng/convertenginestartingtonitrogen.pdf, Natural Gas Star Program, U.S. EPA, Washington DC, 2004.
10. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Automated air/fuel ratio controls (A.1.2.1.15; A.1.2.3.13)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Natural gas-fueled internal combustion engines can provide continuous duty operations over a set range of air to fuel ratios (AFR). Fuel-rich conditions result in greater unburned fuel emissions (primarily methane) and higher CO emissions. Fuel savings and reduced associated emissions can be achieved by installing an automated AFR control system (USEPA, 2004).

Effectiveness: Good

Implementability: The greatest opportunities for system and efficiency improvements are on rich burn, high-speed, turbocharged engines (1,000 hp to 3,000 hp).

Reliability: Good. It was found that operators, in general, run engines in a rich-AFR state would provide the most reliability for field operations (USEPA, 2008).

Maturity: Good

Environmental Benefits: A partner of the Gas STAR program has reduced its fuel consumption by 18% to 24% by installing automated AFR controls on 51 selected engines in its Gulf of Mexico operations. It achieved an average emission reduction of 128 Mcf of methane per unit per year by reducing the engines' fuel consumption (USEPA, 2008).

Cost Effectiveness: A partner of the Gas STAR program reported a reduction in fuel consumption in excess of 2,900 MMcf during a two-year period as the result of installing the REMVue technology on 51 engines, or an average of 78 Mcf per day per engine when adjusted for load. This represents a 39 percent increase in estimated fuel savings (based upon a sample inventory, which yielded a pre-job fuel savings estimate of 56 Mcf per day). The total reported cost was \$6.1 million. Capital costs, including installation, ranged from \$85,000 to \$140,000 per unit, with the average cost for the last two years being \$120,000 per installation. At a nominal value of \$3 per Mcf, the fuel savings was more than \$4.35 million for a calculated payout of 1.4 years (USEPA, 2008).

The partner found that the additional cost of operating the REMVue systems is offset by the reduction in engine maintenance costs. A reduction in NO_x and CO_2 emissions are an added benefit of the system. A post-audit was conducted on 20 percent of the installed base in 2004. Among the engines that were revisited, there were some that were retrofitted as early as 2001. The post audit reviewed pre-, post- and post-post-values for fuel consumption, emissions reductions, availability, and economics based on a normalized gas price. The emissions reduction results showed that unburned hydrocarbons were down 3,549 tons per year, CO_2 emissions were down 2,309 tons per year, and CO emissions were down 83,300 tons per year. There were no changes in NOx emissions. Availability increased 2.25 percent for the 12 months pre-installation versus 12 months post-installation.

- Capital Costs (including installation) : >$10,000
- Operating and Maintenance Costs (annual): Installing system reduces maintenance costs
- Payback (Years): 1-3

Industry Acceptance Level: ChevronTexaco

Limitations: None reported. The technology can communicate/interface with most existing electronic control and telemetry systems.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production; Processing; Transmission)

Technology: Reduce the frequency of engine starts with gas (A.1.2.1.16; A.1.2.3.14)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

Internal combustion engine driven turbine compressors are often started by directing un-ignited pipeline gas through the turbine compressor, rolling the turbine engine prior to ignition. The un-ignited gas, or startup natural gas, is vented to the atmosphere. Operating and maintenance schedules dictate how frequently such turbine engines are restarted. Modifying maintenance practices and operational schedule can reduce emissions (USEPA, 2004).

Effectiveness: It was reported that reducing a refrigeration compressor restart frequency from 9.4 starts per year to 1 start per year, saving 132 Mcf per each avoided restart, or 1.1 MMcf per year (USEPA, 2008).

Implementability: This practice may be employed in operations that have multiple, parallel compressors.

Reliability: Equipment reliability and operational scheduling may apply to other compressors in multi-unit stations.

Maturity: Good

Environmental Benefits: Methane emission reduction

Cost Effectiveness: Methane emission reductions of 132 Mcf per year apply to one turbine engine startup by rolling with un-ignited pipeline gas as reported by a partner. While there are no capital costs, there are potential hidden costs associated with prolonging compressor run times between scheduled preventive maintenance activities, and direct O&M costs associated with improving the maintenance and reliability of engines. In the case of a single engine-driven compressor, generator, or pump at a site, longer run times may lead to production losses from unscheduled shutdowns (USEPA, 2004).

- Capital Costs (including installation): <$1,000
- Operating and Maintenance Costs (annual): <$100
- Payback (Years): 0-1

Industry Acceptance Level: PECO Energy Company

Limitations: Compressors must have flexible operating and routine maintenance schedules.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production)

Technology: Inspection and maintenance - pipeline leaks (A.1.2.1.17)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

This directed inspection and maintenance option is to survey pipelines in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (pipeline leaks)[1]	5	100	60	2	$22.78	$34.18	$8.21

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Annual O&M cost is relatively high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production)

Technology: Inspection and maintenance - equipment and facilities (A.1.2.1.18)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

This directed inspection and maintenance option is to survey facilities and equipment in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (facilities & equipment)[1]	5	-	33	1-3	\$193.25	\$289.88	\$6.82

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital and O&M costs are high.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production)

Technology: Inspection and maintenance - chemical inspection pumps (A.1.2.1.19)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

This directed inspection and maintenance option is to survey chemical inspection pumps in the production sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (chemical inspection pumps)[1]	5	-	40	1-2	$123.14	$6.82	$6.82

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is high.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Production)

Technology: Inspection and maintenance - enhanced (A.1.2.1.20)

Description of the Technology:
In the United States and worldwide, many efforts have been made to identify and implement mitigation options to reduce methane emissions from the natural gas sector (USEPA, 2003). For example, the Natural Gas STAR program is a voluntary partnership between US EPA and the oil and gas industry to identify and implement cost-effective technologies and measures to reduce methane emissions. The measures to reduce methane emissions from the natural gas systems can be grouped into the following mitigation strategies: prevention, recovery and re-injection, recovery and utilization, and recovery and incineration (Hendriks & de Jager, 2001).

This option is a more aggressive inspection and maintenance program with increasing frequency to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (enhanced)[1]	5	-	50	0-1	$246.40	$344.96	$6.82

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital and O&M costs are high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Replacement of reciprocating engines by gas turbines (A.1.2.3.15)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This option replaces natural gas reciprocating engines with natural gas turbines. The turbines have a better combustion efficiency than gas turbine, and, thus, methane emissions are reduced (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Replace reciprocating engines with gas turbines[1]	20	-	90	0-27	\$166.52	\$8.30	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Reciprocating compressor rod packing - Static-Pac (A.1.2.3.16)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

Use Static-Pac® seal or Emissions Packing System® to reduce fugitive losses from compressors when they are placed in the standby mode. An automatic controller activates when the compressor is shutdown to wedge a tight seal around the shaft (USEPA, 2004). Use of Seal Assist System® allows compressor rod seal leaks to be captured and used to fuel IC engine at the compressor station (IEA, 2001).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Reciprocating compressor rod packing (Static-Pac)[1]	1	100	21	6	$14.58	$0.56	$8.53

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Non reported.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Replace wet seals with dry seals on centrifugal compressors (A.1.2.3.17)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

Some centrifugal compressors are fitted with wet seals that circulate oil at the seal face to prevent gas emissions. Dry seals use high-pressure gas to ensure sealing and emit much less methane in comparison to the wet-seal systems (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace wet seals with dry seals on centrifugal compressors[1]	5	-	69	4-6	\$96.68	-\$25.38	\$6.99

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$

IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is relatively high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Alter start-up procedure during maintenance - compressors (A.1.2.3.18)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

Instead of shutting down compressors during monthly cleaning maintenance, deionized water is sprayed into the compressors while the compressors are still on-line (running). This procedure can reduce the required number of compressor start-ups/depressurizations per year (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Alternating start-up procedure during maintenance[1]	1	100	100	3	\$0.00	\$0.00	\$4.47

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: None reported.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Catalytic converter (A.1.2.3.19)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

A catalytic converter can be used as an after-burner to reduce methane emissions resulting from incomplete combustion (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Catalytic converter[1]	10	-	56	5-8	$91.46	$4.82	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is relatively high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Automate systems operation to reduce venting (A.1.2.3.20)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

Transmission pipelines often have multiple compressor stations with five to ten compressors at each station. Where these compressors have older ignition systems, shutdowns and restarts result in blowdown and gas pneumatic starter emissions that release excessive amounts of methane to the atmosphere. Employing automatic control systems on compressor ignition systems can increase the operational efficiency and reliability of the compressor and also reduce methane emissions (USEPA, 2004).

Effectiveness: One partner of the Natural Gas STAR program reported methane savings of 11,092 Mcf per year over 3 years for multiple applications (USEPA, 2008).

Implementability: This option is applicable to all electrified transmission stations.

Reliability: Methane emissions savings of 20 Mcf per year are estimated for a 3,000 HP reciprocating compressor that requires three attempts to start up and one avoidable blowdown per year (USEPA, 2008).

Maturity: Good

Environmental Benefits: Methane emission reduction

Cost Effectiveness: This technology typically has a quick payback. The one-time capital cost for installing a PLC on a reciprocating compressor is justified by the lower operation and maintenance costs rather than gas savings. PLCs reduce methane emissions by providing a better service factor and fewer compressor surges, reducing the amount of methane that is vented to the atmosphere (USEPA, 2008).

- Capital Costs (including installation): $1,000-$10,000
- Operating and Maintenance Costs (annual): $100-$1,000
- Payback (Years): 0-1

Industry Acceptance Level: Louisville Gas and Electric Company; Natural Gas Pipeline Company (now Kinder Morgan, Inc.)

Limitations: An electrical power supply is required to operate the automatic systems.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Replace compressor cylinder unloaders (A.1.2.3.21)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

Compressor cylinder unloaders are used to 1) reduce the machine's start-up load, 2) prevent an overload when there is an upset in operating conditions, and 3) control gas volumes due to fluctuations in rate requirements. Many older reciprocating engine-powered compressors are equipped with outdated or worn cylinder unloaders that continuously leak natural gas even when regularly maintained. Replacing the cylinder unloaders with a design that utilizes a balanced piston that avoids chatter and minimizes the pressure required for operation can reduce emissions (USEPA, 2004).

Effectiveness: A partner of the Natural Gas STAR program reported that a total of 14 MMcf per year of methane emissions were eliminated by replacing the worn unloaders on four compressors with those of a new design at one of their compressor stations (USEPA, 2008).

Implementability:
Compressor cylinder unloader replacement is applicable to compressors equipped with original unloaders that are experiencing maintenance problems (USEPA, 2008).

Reliability: The installation of the new compressor unloaders was approved on the basis of cost effectiveness, design, and safety.

Maturity: Good

Environmental Benefits: Methane emission reduction

Cost Effectiveness: The cost of a new unloader is less expensive than repairing the manufacturer equipped original ones. The partner realized estimated savings in excess of $50,000 per unit per year. The savings include the value of the previously vented gas, reduced safety risks, and maintenance costs. The capital and labor costs to install the unloaders is $40,000 to $50,000 per unit (USEPA, 2008). Payout is in 0 to1 year. Capital costs to replace and install the new unloaders were reported to be $40,000 to $50,000 per unit. However, these costs are justified based on the relatively short pay-back period and reduced O&M costs. Replacement also resulted in fewer unscheduled shutdowns and reduced methane emissions. The partner has plans to replace original unloaders on compressors at other stations (USEPA, 2008).

- Capital Costs (including installation) : >$10,000
- Operating and Maintenance Costs (annual) : <$100
- Payback (Years): 0-1

Industry Acceptance Level: Louisville Gas and Electric Company; Natural Gas Pipeline Company (now Kinder Morgan, Inc.)

Limitations: Re-piping of control lines and personnel trained in the proper maintenance of the new unloaders.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
8. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
9. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Other options for methane reductions related to compressors (A.1.2.3.22)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

There are other options for reducing methane emissions from compressors: they include:

- Using hydraulically-powered valve actuators (compressors) – Valve actuators are typically powered by natural gas, which is released during the valve movement. They can be replaced with locally-mounted hydraulic actuator systems and methane emissions from this source will be eliminated (Hendriks & de Jager, 2001).
- Recompression of gas during maintenance (compressors) – Emissions can be reduced through recompression of emissions during maintenance by using a portable compressor unit and re-routing them back to the system (Hendriks & de Jager, 2001).
- Reduced flushing of engines at start-up and shut-down (compressors) – It has been reported from investigation of several gas-transporting companies that flushing compressors or engines before start-up is not required. Formation of an explosive mixture is prevented by the overpressure in the system (Hendriks & de Jager, 2001).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Data are not available.

Industry Acceptance Level: Good

Limitations: None reported

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Inspection and maintenance - pipeline leaks in transmission (A.1.2.3.23)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This directed inspection and maintenance option is to survey pipelines in the transmission sector to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (pipeline leaks in transmission)[1]	5	100	60	<1	$786.60	$1,180	$8.53

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Capital and O&M costs are high per unit of methane emission reduction.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Inspection and maintenance - compressor stations (A.1.2.3.24)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This directed inspection and maintenance option is to survey compressor stations in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (compressor stations)[1]	5	100	13	4	\$0.57	\$1.86	\$8.53

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: None reported

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

18. **Non-CO_2 Greenhouse Gases:** Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Inspection and maintenance - compressor stations, enhanced (A.1.2.3.25)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This option is a more aggressive inspection and maintenance program with increasing frequency to survey compressor stations in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (compressor stations - enhanced)[1]	5	-	20	2-4	\$0.40	\$2.43	\$7.08

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2-Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Good

Limitations: None reported

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Inspection and maintenance - storage wells (A.1.2.3.26)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This directed inspection and maintenance option is to survey storage wells in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (storage wells)[1]	5	100	33	<1	$38.50	$38.50	$8.53

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: Annual O&M cost is relatively high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Processing; Transmission)

Technology: Inspection and maintenance - storage wells, enhanced (A.1.2.3.27)

Description of the Technology:
Natural gas produced from gas fields needs to be transported to distribution systems, power plants, or chemical plants through high-pressure pipelines. Compressor stations, which contain large reciprocating engines and turbine compressors, are used to move the gas throughout the United States. Natural gas is also injected and stored in subsurface formations, or liquefied and stored in aboveground tanks to meet the fluctuations in gas demand. Sources of methane emissions include emissions from compressors, metering, and regulating stations, dehydrators, and pneumatic devices (USEPA, 2006a).

This option is a more aggressive inspection and maintenance program with increasing frequency to survey storage wells in the processing and transmission sectors to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (storage wells - enhanced)[1]	5	-	50	<0.5	\$38.59	\$38.59	\$7.08

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Annual O&M cost is relatively high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Distribution)

Technology: Electronic monitoring at large surface facilities (A.1.2.4.1)

Description of the Technology:
Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

To ensure that both peak and non-peak operating pressures are met; natural gas distribution systems typically operate at gas pressures that are higher than necessary. Use of electronic monitoring can match the distribution system pressure with real time demand and, thus, reduce methane emission (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Electronic monitoring at large surface facilities[1]	5	100	95	6	$28.07	$4.68	$11.37

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005); 2: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Good

Limitations: None reported.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
18. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
19. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Distribution)

Technology: Replacement of cast-iron/unprotected steel pipeline (A.1.2.4.2)

Description of the Technology:
Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

Cast iron and unprotected steel pipeline are prone to corrosion and leaks. They should be replaced with non-corrosive materials that will reduce methane losses from the distribution system (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replacement of cast iron/unprotected steel pipeline[1]	5	-	95	6-10	$17,259	$0.86	$9.74

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is very high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Distribution)

Technology: Replacement of unprotected steel services (A.1.2.4.3)

Description of the Technology:
Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

Unprotected steel services are prone to corrosion and leaks. They should be replaced with non-corrosive materials, such as plastic or protected services, that will reduce methane losses from the distribution system (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replacement unprotected steel services[1]	5	-	95	3-4	$410,830	$82.17	$9.74

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$

1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital cost is extremely high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Distribution)

Technology: Inspection and maintenance - pipeline leaks (A.1.2.4.4)

Description of the Technology:
Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

This directed inspection and maintenance option is to survey pipelines at the distribution facilities to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inspection and maintenance (pipeline leaks)[1]	5	100	26	9	$4.88	$5.76	$11.30

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2004) & CEC (2005)

Industry Acceptance Level: Good

Limitations: None reported

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) “U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively”, *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) “Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers”, *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) “Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis”, A final report to European Commission.
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Natural Gas Systems (Distribution)

Technology: Inspection and maintenance - enhanced (A.1.2.4.5)

Description of the Technology:
Distribution pipelines take the high-pressure gas from the natural gas transmission systems to individual end-users. There were over one million miles of distribution mains in the United States. Distribution system emissions result mainly from fugitive emissions from gate stations and non-plastic piping.

This option is a more aggressive inspection and maintenance program with increasing frequency at the distribution facilities to identify and quantify leak sources and perform maintenance/repair on leaks that are most cost-effective to repair. It costs more, but also achieves greater saving by reducing leaks further (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefit s
Inspection and maintenance (enhanced)[1]	5	-	66	1-12	$21.14	$21.08	$9.42

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Higher O&M cost than regular inspection and maintenance.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. Fernandez, R.; Lieberman, D.; Robinson, D. (2004) "U.S. Natural Gas STAR Program Success Points to Global Opportunities to Cut Methane Emissions Cost-Effectively", *Oil & Gas J.* July 12.
6. Fernandez, R.; Petrusak, R.; Robinson, D.; Zavadil, D. (2005) "Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers", *J. Petroleum Technology*, June.
7. Hendriks, C.; de Jager, D. (2001) "Economic Evaluation of Methane Emission Reductions in the Extraction, Transport and Distribution of Fossil Fuels in the EU: Bottom-up Analysis", A final report to European Commission.
8. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
10. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
11. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
13. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
14. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
15. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
16. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
17. U.S. Environmental Protection Agency (2008), Natural Gas Star Program, http://www.epa.gov/gasstar/index.htm, U.S. EPA, Washington DC, 2004.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Stationary Combustion

Technology: Options in general (A.1.3)

Description of the Technology:
Stationary combustion includes all fuel combustion activities from fixed sources (versus mobile combustion). For stationary sources, methane may result from incomplete combustion of fuels. Methane is produced in small quantities from fuel combustion due to incomplete combustion of hydrocarbons in fuel. The production of CH_4 is a function of the temperature in the boiler/kiln/stove. In large facilities and industrial applications, the combustion is more efficient and the emission rate is very low. On the other hand, emission rates from smaller combustion sources are often higher, particularly when smoldering occurs. The highest rates of CH_4 emissions from fuel combustion occur in residential applications such as small stoves and open burning (USEPA, 2006a).

Little information regarding technological options for methane emission reduction in this sector was found from the literature search. Basically, reducing energy demand and improving combustion efficiency can reduce methane emissions from this sector.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

5. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
6. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
7. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
8. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
9. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Mobile Combustion

Technology: Options in general (A.1.4)

Description of the Technology:
Methane emissions from mobile sources depend on methane content of the motor fuel, the amount of hydrocarbons remained un-burned in the engine exhaust, the engine type, and post-combustion controls. In vehicles without emission controls, the amount of CH_4 emitted is highest at low speeds and when the engine is idle. Poorly tuned engines would have higher CH_4 emissions (USEPA, 2006a).

Little information regarding technological options for methane emission reduction in this sector was found from the literature search. Basically, using alternative fuels, reducing travel, and improving vehicle efficiency can reduce methane emissions from this sector (CARB, 2004).

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

6. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
7. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Abandoned Underground Coal Mines

Technology: Options in general (A.1.5)

Description of the Technology:
Active underground coal mines contribute a large share of methane emissions in the United States. As mines mature and coal seams are mined through, mines will be closed and abandoned. Many abandoned mines were sealed and some were flooded through groundwater intrusion or by surface water. Some abandoned coal mines are vented to the atmosphere to prevent the buildup of methane gas. After an initial decline, abandoned coal mines can liberate methane gas at a steady-state rate for a long period of time (USEPA, 2006a).

Although there are no active coal mines in California, there were coal-mining activities in the past. Methane emissions from abandoned coal mines were not included in the most recent inventory report by CEC (CEC, 2006). Flaring of the collected off-gases is a viable option to reduce methane emissions from abandoned underground coal mines.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
7. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Industrial Processes

Technology: Options in general (A.2)

Description of the Technology:
Active underground coal mines contribute a large share of methane emissions in the United States. As mines mature and coal seams are mined through, mines will be closed and abandoned. Many abandoned mines were sealed and some were flooded through groundwater intrusion or by surface water. Some abandoned coal mines are vented to the atmosphere to prevent the buildup of methane gas. After an initial decline, abandoned coal mines can liberate methane gas at a steady-state rate for a long period of time (USEPA, 2006a).

Although there are no active coal mines in California, there were coal-mining activities in the past. Methane emissions from abandoned coal mines were not included in the most recent inventory report by CEC (CEC, 2006). Flaring of the collected off-gases is a viable option to reduce methane emissions from abandoned underground coal mines.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
7. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improvements to animal husbandry/livestock reduction (A.3.1.1)

Description of the Technology:
Livestock numbers are the major determinant of methane emission from pastoral agriculture, and it is implicit that reducing numbers is the simplest way to reduce emission. Improvements to animal husbandry focus on reducing methane emissions per unit product (meat, milk, wool, etc.) rather than emissions per animal as the most cost-effective means of reducing overall methane production. Hence, it aims to reduce the herd size while sustaining the same output. Together with supplementation to improve efficiency of feed utilization and increase product output, this may reduce methane production per unit of milk or meat by a factor of 4-6. Provided animal numbers decrease, as demand is met, the production of methane from the large populations of animals fed poor-quality forages could be reduced to below 50%, and perhaps even to as low as 25% of its present rate.

Effectiveness: Good

Implementability: This option is especially effective in developing countries, which account for more than half ruminant numbers; also in semi-arid regions of developed countries where reproductive performance and meat and dairy productivity are limited by food quality (Leng, 1991).

Reliability: One of the basic options to reduce emissions from this sector.

Maturity: Fair

Environmental Benefits: Methane emission reduction

Cost Effectiveness: This can be a cost effective option since the cost of feed would decrease according to the decrease in animal size (US Climate Change, 2005).

Industry Acceptance Level:

Limitations: Reduction of livestock will obviously have implications for farm profitability and for the size of the agricultural sector; it may also reduce the supply of farm product such as meat and milk (Bates, 2001). This is not an acceptable solution as a stand-alone option; however, it may be possible to reduce methane emissions by combining with improvements in animal efficiency with lower livestock numbers (O'Hara *et al.*, 2003). Some countries are heavily dependent on their livestock industries for generating national income, and the imposition of regulations aimed at reducing livestock numbers would not be well received by the farming industry (US Climate Change, 2005).

Sources of the information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

3. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
4. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. Leng, R. A. (1993) “Quantitative ruminant nutrition - A green science”, Australian Journal of Agricultural Research, 44: 363-80, 1993.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improved feed conversion efficiency (A.3.1.2)

Description of the Technology:
Several methods can be used to improve feed conversion efficiency and, consequently, reduce methane emissions:

- Improved level of feed intake – An increase in level of feed intake can change the volatile fatty acid (VFA) content in the rumen and less acetate and more propionate is formed resulted in lower methane production and emissions (de Jager *et al.*, 2001).
- Replacing roughage with concentrates – Roughage contains a high level of structural carbohydrates (fibers). Replacing part of the roughage in the animal diet with concentrates can improve propionate generation and reduce methane production and emissions (Cole *et al*., 1996; Cole *et al*., 1997; de Jager *et al.*, 2001).
- Changing composition of concentrates – Adding unsaturated fatty acid and/or lipids (high fat diet) to the animal diet can increase the formation of propionate and reduce methane production and emissions (de Jager *et al.*, 2001; Bates, 2001).
- Alkali/ammonia/urea treatment of low quality roughage – The digestibility of low quality roughages such as straw can be improved by treatment using chemicals such as sodium hydroxide, ammonium hydroxide, and urea. Substantial methane reduction is feasible in combination with livestock reduction (de Jager *et al.*, 2001; Bates, 2001).
- Chopping of low quality crop by-products – Physical modifications of straws and other crop-by-product by chopping and milling can also improve feed intake and animal performance and result in less methane production and emissions (Cole *et al*., 1996; Cole *et al*., 1997; de Jager *et al.*, 2001).
- Wrapping and preserving rice straw – By wrapping freshly-cut and urea-treated straw in bales, its nutritive value can be better retained and spoilage is prevented (de Jager *et al.*, 2001; Bates, 2001).

Effectiveness: Good

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Fair

Limitations: None reported.

Sources of the information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, a final report to European Commission.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) “Global Estimates of Potential Mitigation of Greenhouse Gas Emissions by Agriculture”, *Nutrient Cycle in Agroecosystems*, 52, 221-228.
4. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) “Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions” in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
7. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
8. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
9. Leng, R. A. (1993) “Quantitative ruminant nutrition - A green science”, Australian Journal of Agricultural Research, 44: 363-80, 1993.
10. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improving animal productivity through the use of growth hormones (A.3.1.3)

Description of the Technology:
Naturally occurring hormones and synthetic compounds have been identified or developed to achieve production-enhancing effects. Use of these hormone compounds reduce methane emissions through improved feed efficiency and reduced time to slaughter. Although the use of growth hormones is currently considered controversial, a large number of compounds such as recombinant bovine somatropin (rbST), antibiotics and anabolic steroids are currently being used and tested as feed additives for ruminants (de Jager *et al.*, 2001; O'Hara *et al.*, 2003; Bates, 2001).

Effectiveness: Bovine somatotropin (BST) growth hormone was observed to decrease methane emissions in dairy herd. BST has been observed to decrease CH_4 emissions by 9% in US dairy herd.

Implementability: Applicability is limited in some countries.

Reliability: Fair

Maturity: Fair

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Fair

Limitations: Not approved to use in Canada due to concerns over hormones in milk and meat products.

Sources of the information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
3. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
4. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
5. Peter O'Hara, John Freney, Marc Ulyatt (2003), "Report prepared for the Ministry of Agriculture and Forestry on behalf of the Governor", Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council, http://www.maf.govt.nz/mafnet/rural-

nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P3045_283655, May2003.

6. Reducing Greenhouse Gas Emissions from Livestock Agriculture in Manitoba, MANITOBA CLIMATE CHANGE TASK FORCE by Dr. Karin Wittenberg Head, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2 and Dinah Boadi, Research Associate, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO$_2$ Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improving genetic characteristics (A.3.1.4)

Description of the Technology:

Genetic manipulation of rumen bacteria and/or animals can potentially reduce methane emissions; however, ethical aspects and public acceptance are topics to be dealt with (Cole *et al*., 1996; de Jager *et al*., 2001).

Effectiveness: Unknown

Implementability: Low

Reliability: Unknown

Maturity: Low

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Ethical aspects and public acceptance are topics to be dealt with.

Sources of the information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, a final report to European Commission.
2. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) “Global Estimates of Potential Mitigation of Greenhouse Gas Emissions by Agriculture”, *Nutrient Cycle in Agroecosystems*, 52, 221-228.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) “Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions” in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO$_2$ Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708

7. Peter O'Hara, John Freney, Marc Ulyatt (2003), “Report prepared for the Ministry of Agriculture and Forestry on behalf of the Governor”, Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P3045_283655, May2003.

8. Reducing Greenhouse Gas Emissions from Livestock Agriculture in Manitoba, MANITOBA CLIMATE CHANGE TASK FORCE by Dr. Karin Wittenberg Head, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2 and Dinah Boadi, Research Associate, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708

9. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

11. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).

12. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.

13. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improving nutrition through strategic supplementation (A.3.1.5)

Description of the Technology:

There are many methods can be used to improve nutrition through strategic supplementation and, consequently, reduce methane emissions. They include:

- Defaunation – One way to manipulate the rumen microbial population is defaunation, in which all protozoa (typically 50% of the total microbial mass in rumen) are eliminated. Defaunating agents such as manoxol, teric, alkanate 3SL3 and sulphosuccinate can reduce methane emission.
- Probiotics – Probiotics are microbial feed additives that contain live cells and a growth medium. These can stimulate milk yield and increase weight gain (Bates, 2001; de Jager *et al.*, 2001).
- Antimethanogen – Certain halogenated compounds such as chloroform, carbon tetrachloride, and methylene chloride can inhibit methane production up to 90%; however, they are not suitable as feed additives yet, because of the associated accumulation of hydrogen and their volatile characteristics (de Jager *et al.*, 2001).
- Molasses/urea blocks – Many nutrients must be present in the diet to support the rumen microbial population; ammonia concentration in rumen is often the primary limitation on efficient digestion. Urea added to the diet has been the most effective method of boosting ammonia levels in the rumen. The molasses/urea block (MUB) is easy to use and methane emission reductions per unit product can be as high as 40% (de Jager *et al.*, 2001).
- Molasses/urea blocks with bypass protein – Animals capable of higher yields and faster growth-rates need a greater supply of amino acids. Providing supplements of molasses/urea blocks (MUBs) with by-pass proteins, which can escape degradation in the rumen and are digested in the lower gut, can greatly increase milk yield and weight-gain of animals on straw/forage (de Jager *et al.*, 2001).
- Targeted mineral/protein supplement – Protein and specific minerals may be deficient seasonally or throughout the year. Supplements targeted to these deficiencies can improve productivity and reduce methane emissions (de Jager *et al.*, 2001).

Effectiveness: Defaunation of the rumen has shown a 30 to 45% decrease in methanogenesis (de Jager *et al.*, 2001). The effects of antimethanogens may not last long.

Implementability: There are concerns of adaptation and toxicity to animal and use of defaunating agents and antimethanogens are scarce, if any**.**

Reliability: Low

Maturity: Fair

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Complete defaunation is difficult to achieve on a large scale. There is a fine line between killing the protozoa and killing the animal. The toxicity of many defaunating agents and antimethanogens restricts their routine use. Applicability and toxicity of antimethanogens are the major concern to animals.

Sources of the information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. Leng, R. A. (1993) "Quantitative ruminant nutrition - A green science", Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Improving reproduction (A.3.1.6)

Description of the Technology:

Many ruminants are maintained for purpose of producing offspring. By improving animals' reproductive efficiency, methane emissions per unit product can be reduced. The potential strategies include twinning, embryo transplantation, and artificial insemination, and estrus synchronization (de Jager *et al.*, 2001).

Effectiveness: Unknown

Implementability: Fair

Reliability: Unknown

Maturity: Low

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Maturity of the technologies.

Sources of the information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708

7. Leng, R. A. (1993) “Quantitative ruminant nutrition - A green science”, Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Enteric Fermentation

Technology: Intensive grazing (A.3.1.7)

Description of the Technology:

In a management-intensive grazing system, cattle are frequently rotated between pastures to allow recently-grazed pastures time to regrow and to provide cattle with more nutritious pasture grazing. This option may reduce animal yield, but it will decrease methane emission by an even larger percentage (USEPA, 2006).

Effectiveness: Fair

Implementability: Readily implementable

Reliability: Low

Maturity: Fair

Environmental Benefits: Methane emission reduction

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Potential reduction in animal yield.

Sources of the information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, a final report to European Commission.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) “Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions” in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708

7. Leng, R. A. (1993) “Quantitative ruminant nutrition - A green science”, Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO$_2$ Greenhouse Gases: Methane

Source/Sectors: Agriculture/Manure Management

Technology: Anaerobic digestion systems (A.3.2.1)

Description of the Technology:
In general, measures to mitigate methane emissions from manure management include livestock reduction, prevention of fermentation during stabling, controlled fermentation of manure, composting, and aerobic digestion. The key reduction option is the capture and use of methane emissions through the use of anaerobic digesters that can be farm scale or centralized for the intensive agricultural zones (Lucas *et al.*, 2006). The technological options for anaerobic digestion include covered lagoons, plug flow digesters, and centralized digesters. Controlled anaerobic digestion can be operated in psychrophilic (10-20 ^{o}C), mesophilic (20-40 ^{o}C), or thermophilic (50-60 ^{o}C) range.

Effectiveness: Good

Implementability: Anaerobic digestion technologies can be applied at various scales (i.e., farm or centralized) and require separate effluent storage and a gas use device (US Climate Change, 2005).

Reliability: Anaerobic digesters are practical and often cost-effective for most large dairy and swine farms, especially those located in warm climates. These systems also reduce foul odor and can reduce the risk of ground- and surface-water pollution (US Climate Change, 2005).

Maturity: Good

Environmental Benefits: Methane recovery and utilization for energy generation

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Covered lagoon, not including lagoon cost (large dairy)[1]	15	70	95	29	$42.22	$5.12	$14.27
Covered lagoon, including lagoon cost (large dairy)[1]	15	30	95	29	$56.30	$5.12	$14.27
2-stage plug flow digester (large dairy)[1]	15	1	95	100	$96.38	$5.12	$14.27
Plug-flow digester[1]	15	34	95	100	$69.27	$5.12	$14.27
Covered lagoon, not including lagoon cost (small dairy)[1]	15	70	95	29	$145.67	$5.12	$14.27
Covered lagoon, including lagoon cost (small dairy)[1]	15	30	95	29	$194.09	$5.12	$14.27
Centralized digester[1]	15	4	95	100	$174.67	$26.14	$32.31

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2\text{-}Eq.}$
1: CEC (2005)

Industry Acceptance Level: Fair

Limitations: Utility policies toward independent power producers delay further development of digestion technologies for power generation. The complexity of operation also impedes the market penetration; a centralized operating structure with dedicated expertise may justify this limitation. Moreover, bio-security issues may reduce the potential of these options (US Climate Change, 2005).

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. Leng, R. A. (1993) "Quantitative ruminant nutrition - A green science", Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Manure Management

Technology: Aerobic digestion (A.3.2.2)

Description of the Technology:
In aeration processes, oxygen is transferred to a liquid primarily by mechanical equipment. The equipment serves to (a) provide the oxygen needed by the microorganisms to oxidize the organic matter and (b) keep the solids in suspension by mixing. A residual-dissolved oxygen concentration of at least 1-2 mg/L is an indicator that the rate of oxygen transfer is adequate to satisfy this oxygen demand aerobically for livestock waste. This requirement is usually met by large pumps operating in the range of about 50-125 HP (US Climate Change, 2005).

The methane emission can also be reduced by preventing anaerobic decomposition of manure during stabling of livestock (to keep it more aerobic). The way manure is stored and handled in stables determines the extent of methane production and emission. Higher temperature and longer storage periods favor growth of methanogenic bacteria. Storage of manure outside the stable may result in lower methane production because of lower out-door temperature in a moderate climate (de Jager *et al.*, 2001).

Effectiveness: Good

Implementability: Aeration processes may be feasible for secondary or tertiary treatment of livestock waste, where greater pollution control is desirable – or to further reduce nitrogen availability for crop uptake (US Climate Change, 2005).

Reliability: Good

Maturity: Good

Environmental Benefits: Methane emission reduction

Cost Effectiveness: Expensive
This option requires high investment and operating costs (including energy) to treat waste streams aerobically (US Climate Change, 2005).

Industry Acceptance Level: Aeration processes are basically applied to low-strength and dilute waste streams due to energy requirements. Their use has been limited for livestock liquid and slurry waste streams (US Climate Change, 2005).

Limitations: Aeration processes increase the volume of residual solids depending on the operating conditions necessitating removal and additional management. it may also volatilize 30%-90% of the nitrogen as N_2 or N_2O, which can contribute to global warming and other environmental problems (US Climate Change, 2005).

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, a final report to European Commission.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2

Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. Leng, R. A. (1993) "Quantitative ruminant nutrition - A green science", Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Rice Cultivation

Technology: Water management (A.3.3.1)

Description of the Technology:
All rice in the United States is grown on flooded fields. One of the most important factors affecting methane emissions is the water management system under which rice is grown. Under continuously flooded conditions, rice fields have higher methane emissions than those that are not flooded. Other factors that influence methane emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (USEPA, 2006a).

Specific water management technological options to reduce CH_4 emissions from rice cultivation include:

- Water management – Changes in the water management regime to reduce time over which anaerobic conditions in flooded field occur would reduce methane emissions (Graus *et al.*, 2004). Full midseason drainage may reduce methane emissions (USEPA, 2006b).
- Shallow flooding – In this option, rice paddies are marginally covered by flood water, with the water table fluctuating 5 to 10 cm above and below soil surface (USEPA, 2006b).
- Upland rice – Using upland rice, which can grow in dry land, can eliminate flood water in the field to reduce methane formation and emissions (USEPA, 2006b).

Effectiveness: Fair

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: Methane emission reduction.

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Upland rice production potential at the same levels of input is much lower than wetland rice.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", a final report to European Commission.
2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995.

Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.

4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. Leng, R. A. (1993) "Quantitative ruminant nutrition - A green science", Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. Neue, H. (1993) "Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming", Bioscience 43 (**7**): 466-73.
9. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
12. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Rice Cultivation

Technology: Other options for methane reductions - excluding water management (A.3.3.2)

Description of the Technology:
All rice in the United States is grown on flooded fields. One of the most important factors affecting methane emissions is the water management system under which rice is grown. Under continuously flooded conditions, rice fields have higher methane emissions than those that are not flooded. Other factors that influence methane emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (USEPA, 2006a).

Specific technological options, other than water management, to reduce CH_4 emissions from rice cultivation include:

- Alter the amendments to soils – Adding amendments (e.g., phosphogypsum) to soils to inhibit methanogenesis would reduce methane emissions (Beach et al., 2006; Graus *et al.*, 2004).
- Use of alternative fertilizers – Using an alternative fertilizer (e.g., ammonium sulfate instead of urea) may also reduce methane emissions because sulfate additions to soil can elevate reduction potential, which suppresses methane production (USEPA 2006b; Beach *et al.*, 2006).
- Off-season straw – Shifting straw amendment from in-season to off-season (e.g., apply rice straw two months before rather than in the beginning of rice-growing season) can decrease availability of dissolved organic carbon and, thus, the population of methanogens (USEPA, 2006b).

Effectiveness: Fair

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: Methane emission reduction.

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: May affect the rice production.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, a final report to European Commission.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy

Commissions, CEC-500-2005-121, July 2005.

3. Cole, V.; Cerri, C.; Minami, K.; Mosier, A.; Rosenberg, N. *et al.* (1996) "Chapter 23 – Agricultural Options for Mitigation of Greenhouse Gas Emissions" in Climate Change 1995. Impacts, Adaptions and Mitigation of Climate Change: Scientific-Technical Analyses. IPCC Working Group II, Cambridge Univ. Press.
4. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
5. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/greenhouse-gas-policies/greengas-14.htm#P1797_148161
6. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P4056_323708
7. Leng, R. A. (1993) "Quantitative ruminant nutrition - A green science", Australian Journal of Agricultural Research, 44: 363-80, 1993.
8. Neue, H. (1993) "Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming", Bioscience 43 (**7**): 466-73.
9. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
12. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Agriculture/Field Burning of Agriculture Residues

Technology: Options in general (A.3.4)

Description of the Technology:
Large quantities of agricultural crop residue are produced from farming activities. Crop residue burning is a net source of methane, which is released during combustion (USEPA, 2006a).

The mitigation options for reducing methane emissions from field burning of agricultural residue include improved fire management practices, plowing under, or composting (Gale & Freund, 2002).

Effectiveness: Unknown

Implementability: Unknown

Reliability: Unknown

Maturity: Fair

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: None reported.

Industry Acceptance Level: Fair

Limitations: None reported.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
7. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Land-use Change and Forestry

Technology: Options in general (A.4)

Description of the Technology:
The only potential source for methane emissions in this sector is forest fires. Methane emissions from this sector are not included in the most recent inventory report by CEC (CEC, 2006). No practical technological options for reducing methane emissions in this sector were found in the literature search.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: Not applicable

Cost Effectiveness: None reported.

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
4. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
7. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

8. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
9. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
10. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Landfill gas recovery and utilization - direct gas use/upgrade to natural gas (A.5.1.1)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

In this option landfill gas is recovered and used as a medium BTU fuel for boilers or industrial processes. The gas is directly piped to a near-by user and serves as a replacement fuel. Several methods such as membrane separation can separate carbon oxide and other compounds in landfill gas from methane. The treated gas can be injected to a local natural gas distribution grid. The recovered gas can also be converted to compressed natural gas (CNG), liquefied natural gas (LNG), methanol, or ethanol (US Climate Change, 2005).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Direct gas use (WIP[2] <100,001 tons)[1]	15	0	85	14	$152.91	$4.97	$9.25
Direct gas use (WIP 100,001 – 200,000 tons)[1]	15	0	85	4	$68.57	$3.70	$9.18
Direct gas use (WIP 200,001 – 300,000 tons)[1]	15	0	85	4	$47.44	$3.41	$9.07
Direct gas use (WIP 300,001 – 400,000 tons)[1]	15	33	85	4	$41.74	$3.51	$9.36
Direct gas use (WIP 400,001 – 500,000 tons)[1]	15	50	85	8	$37.73	$3.63	$9.34
Direct gas use (WIP 500,001 – 1,000,000 tons)[1]	15	29	85	23	$23.09	$3.29	$9.34
Direct gas use (WIP 1,000,000+ tons)[1]	15	31	85	43	$15.00	$3.13	$9.16

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005); 2: WIP = waste-in-place

Industry Acceptance Level: Good

Limitations: Unit capital cost is higher for smaller landfills.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Landfill gas recovery and utilization - electricity generation (A.5.1.2)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

In this option, recovered landfill gas is used for electricity generation projects.

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Electricity (WIP[2] <100,001 tons)[1]	15	100	85	14	$169.53	$6.59	$7.81
Electricity (WIP 100,001 – 200,000 tons)[1]	20	100	85	4	$88.04	$5.31	$7.76
Electricity (WIP 200,001 – 300,000 tons)[1]	20	100	85	4	$67.39	$5.00	$7.67
Electricity (WIP 300,001 – 400,000 tons)[1]	20	67	85	4	$62.57	$5.15	$7.91
Electricity (WIP 400,001 – 500,000 tons)[1]	20	50	85	8	$58.70	$5.27	$7.89
Electricity (WIP 500,001 – 1,000,000 tons)[1]	20	71	85	23	$44.54	$4.94	$7.90
Electricity (WIP 1,000,000+ tons)[1]	20	69	85	43	$36.27	$4.74	$7.74

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005); 2: WIP = waste-in-place

Industry Acceptance Level: Good

Limitations: Unit capital cost is higher for smaller landfills.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Anaerobic digestion (A.5.1.3)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

Anaerobic digestion utilizes a reactor vessel to enhance natural decomposition under anaerobic environment. The temperature, moisture content, and pH are maintained close to their optimal values. The generated methane can be used to produce heat and/or electricity (USEPA, 2004). Anaerobic digestion (includes additional cost for waste separation) is similar to the above-mentioned option, anaerobic digestion, but this option includes the cost of source separation of waste prior to disposal in the anaerobic digestion system (IEA, 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Good

Maturity: Fair

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Anaerobic digestion[1]	15	-	95	100	\$400.98	\$67.61	\$8.74
Anaerobic digestion (with additional cost for waste separation)[1]	15	-	95	100	\$484.91	\$125.89	\$5.25

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004);

Industry Acceptance Level: Low

Limitations: Capital and O&M costs are very high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) "Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands", *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) "Methods for Reducing Methane Emissions from Natural Gas Systems", *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO$_2$ Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Composting (A.5.1.4)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

This option involves degradation of organic matter under aerobic conditions. It requires separating organic matter from the waste stream. Finished compost has a market value, used to enhance soil in horticulture/landscape and agricultural sites (USEPA, 2004; IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Composting[1]	15	-	100	100	\$359 - \$424	\$81.59 - \$93.25	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{\text{CO2-Eq.}}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital and O&M costs are very high.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO$_2$ Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Mechanical biological treatment (A.5.1.5)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

In this option, the whole waste stream is composted in order to degrade the organic fraction anaerobically. The inorganic fraction needs to be disposed of in a landfill (USEPA 2003; IEA, 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Mechanical biological treatment[1]	15	-	95	100	$359.02	$121.23	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Capital and O&M costs are very high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.

5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf*. November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Increased oxidation (A.5.1.6)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

In this option, methane emissions are reduced by the top capping and restoration layers of the landfills. A clay cap minimizes methane leakage, while the landfill soil cover above the clay cap oxidizes the escaping methane (USEPA, 2004; Inamori *et al.*, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Increased oxidation[1]	50	-	44	100	$465.43	$0.63	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$

1: IEA (2003) & USEPA (2004)

Industry Acceptance Level: Fair

Limitations: Unit capital cost is very high.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. Tingley, K.A.; Fernandez, R. (2003) “Methods for Reducing Methane Emissions from Natural Gas Systems”, *Proc. 3rd International Methane and Nitrous Oxide Mitigation Conf.* November 17-21, Beijing, China.
9. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
10. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
11. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
12. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Landfills

Technology: Other options for methane reductions related to landfills (A.5.1.7)

Description of the Technology:
Landfills are the largest anthropogenic source of methane emissions in the United States. Key reduction options for methane emissions from landfills are reduction of the amount of organics deposited into landfills, and energetic use or flaring of landfill gas (Lucas *et al.*, 2006).

In addition to direct gas use, electricity generation, anaerobic digestion, composting, mechanical biological treatment, and increased oxidation, there are other technological options available to reduce methane emissions from landfills, they include:

- Optimize and enhance landfill gas formation – Moisture is pivotal for biological activities. An increase of moisture content and enhancement of moisture movement accelerate the speed and increase the completeness of conversion of organics to landfill gas. Consequently, control of moisture (e.g., by infiltrating water or leachate) enables control over landfill gas production and probably emissions (de Jager *et al.*, 2001).
- Waste treatment in bioreactors (the sustainable landfill) – An alternative to traditional sanitary landfill is waste treatment in a bioreactor in which biological, chemical, and physical processes occur in a controlled way. In this approach waste is deposited in relatively small and shallow compartments with an impermeable bottom liner. The waste filling period is kept short, one year at maximum, to prevent the on-set of methanogenesis before the top liner is installed. After the installation of the top liner, biological process in the waste is accelerated through infiltration and recirculation of leachate (Delhotal *et al.*, 2006; de Jager *et al.*, 2001). They are currently two bioreactor processes - anaerobic and aerobic. Hybrid bioreactors employ both methods (US Climate Change, 2005)
- Aerobic landfilling or aerobic pretreatment – Maintaining aerobic conditions in the landfill or the aerobic pretreatment is a way for reducing methane emissions. One option to maintain aerobic conditions is to inject compressed air, 3 to 7 bar, into the landfill and position several extraction wells in strategic locations to collect the product gas mixture. If aerobic pretreatment is practiced, the biodegradable organics are converted to carbon dioxide and the waste will have less or negligible methane formation potential after landfilling (de Jager *et al.*, 2001).
- Source reduction – Methane is the end-product of waste degradation in landfills. Reducing the amount of degradable waste landfilled will reduce methane emissions. It can be achieved from practices such as waste prevention, recycling, composting, fermentation, or waste incineration (de Jager & Blok, 1996).

Effectiveness: Fair

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: None reported.

Industry Acceptance Level: Fair

Limitations: None reported.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
3. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) “Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands”, *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
11. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
12. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
13. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Methane

Source/Sectors: Wastes/Wastewater Treatment

Technology: Options in general (A.5.2)

Description of the Technology:
During collection and treatment, wastewater and sludge may be accidentally or deliberately managed under anaerobic conditions. Under these conditions, methane would be formed as a by-product.

Key reduction options for methane emissions from wastewater are addition of more wastewater treatment plants, aerobic wastewater treatment, and recovery of methane from anaerobic wastewater treatment processes (Lucas *et al.*, 2006). Specific technological options to reduce CH_4 emissions from wastewater include the:

- Aerobic wastewater treatment – Aerobic wastewater treatment processes such as activated sludge systems, oxidation ditch, trickling filters, waste stabilization ponds, and others can biodegrade organics and reduce the methane emission potential.
- Upgrading of existing overloaded or under-aerated wastewater treatment plants – Implementation of this option will greatly reduce the methane emission potentials from those plants (de Jager *et al.*, 2001).
- Anaerobic treatment – Anaerobic treatment can also be applied to wastewater, especially that of high organic concentrations. The methane gas produced will be collected and then destructed or used for electricity generation (USEPA, 2006b).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces methane emissions.

Cost Effectiveness: None reported.

Industry Acceptance Level: Good

Limitations: None reported.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.

3. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
4. de Jager, D.; Blok, K. (1996) "Cost Effectivess of Methane-Reducing Measures for Methane in the Netherlands", *Energy Convers. Mgmt.* 37(6-8), 1181-1186.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
7. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
8. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (1999) "Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions", United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.
10. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
11. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.epa.gov/methane/appendices.html (in Excel file).
12. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
13. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

APPENDIX B

Technological Options for Emission Reduction of Nitrous Oxide

1. - Agriculture
    1.1 - Agricultural Soil Management
        1.1.1 - Improving nitrogen utilization efficiencies
        1.1.2 - Inhibition of nitrous oxide formation
    1.2 - Manure Management
    1.3 - Field Burning of Agricultural Residues
2. - Energy
    2.1 - Mobile Combustion
    2.2 - Stationary Combustion
    2.3 - Municipal Solid Waste Combustion
3. - Industrial Processes
    3.1 - Nitric Acid Production
        3.1.1 - High-temperature catalytic reduction
        3.1.2 - Low-temperature catalytic reduction
        3.1.3 - Non-selective catalytic reduction (NSCR)
        3.1.4 - Options other than catalytic reduction
4. - Solvent and Other Product Uses
5. - Land-Use Changes and Forestry
6. - Waste

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Agriculture/Agricultural Soil Management

Technology: Improving nitrogen utilization efficiencies (B.1.1.1)

Description of the Technology:
Several agricultural activities increase mineral nitrogen availability in soils for nitrification and denitrification and ultimately increase the amount of N_2O emissions (USEPA, 2006a). Although most of the N_2O emissions from agricultural activities are from soils, the emission flux of N_2O per unit surface area of soil is small and varies greatly across time and space. The flux rate depends significantly on soil type, climate conditions, and soil management practices (IEA, 2000). Basically, there are two types of strategies and related technological options that are applicable to emission reduction of N_2O from agricultural soils. The first type uses measures that improve efficiencies in nitrogen utilization, and the second type inhibits the formation of nitrous oxide (Kowalenko, 1999). It should be noted that there are overlaps in these two types. For example, the use of the nitrification inhibitor and change in irrigation practices are also measures for improving nitrogen fertilizer efficiencies in the field.

With regards to improving nitrogen utilization efficiencies to reduce N_2O emission from agricultural soil, many technological options and practices have been mentioned in literature. However, many of them were mentioned without detailed discussion and information. In addition, very few studies include cost data for implementing mitigation options (DeAngelo *et al.*, 2006). The economic potential for nitrous oxide emission reduction probably is low, except perhaps for efficient fertilizer use (Blok and de Jager, 1994). Below are a list and a brief description of the technological options and practices found from the literature search:

- Soil testing to optimize nitrogen application rate – More nitrogen is usually applied to soil than is needed because of the concern of production lost by under-fertilizing (Branosky & Greenhalgh, 2007). Soil nitrogen testing can be used to help growers adjust nitrogen application rates to match site-specific conditions and have more efficient use of fertilizers (IEA, 2000; O'Hara *et al.*, 2003). The abatement cost for the soil testing option is approximately \$5/$MT_{CO2\text{-}Eq.}$ (Gale and Freund, 2002).
- Controlled released fertilizers (CRFs) – The CRFs are intended to release nutrients at a rate that corresponds with nutrient demand of growing crops. Typically, there is a physical barrier (e.g., a polymer coating) that decreases the rate of nutrient release into the soil. The coatings can be adjusted to match the release rate to the requirements of specific plants (Dalal *et al.*, 2003; IEA, 2000). However, as the release of nutrients from CRFs depends on several factors (temperature, water, root structure), this may be difficult to achieve in practice (Bates, 2001). The abatement cost for the CRF option is approximately \$50/$MT_{CO2\text{-}Eq.}$ (Gale and Freund, 2002).
- Changes in the timing and/or frequency of fertilizer application – The use of fertilizer will be more efficient when the fertilizer application coincides with the period of rapid plant uptake. Several applications of small amounts (split applications) during the growing season would be a more effective means of supply nitrogen for plan growth and the N_2O emission loss should be smaller (IEA, 2000). However, it may not always be practical (Bates, 2001).
- Matching fertilizer nitrogen type to season and general weather pattern – Nitrate-based fertilizer is less stable in soil than the ammonia-based fertilizer. When leaching potential is high, ammonia-based fertilizer should be used. An example is to use ammonium-based fertilizer when it is wet and nitrate-based fertilizer when it is dry (McTaggert *et al.*, 1994).

- Crop rotation options – Crop rotation entails the growing of different annual or perennial crops in a given field. It is often used as a strategy for improving soil conditions as well as a component of pest control. Corn-alfalfa rotations might also be an effective means of reducing the use of synthetic fertilizers (IEA, 2000).
- Substitute manure for chemical fertilizer – If commercial fertilizers are replaced with livestock manure, N_2O emission from chemical fertilizers can be reduced without increasing emissions from manure (IEA, 2000; de la Chesnaye *et al.*, 2001). Early application and immediate incorporation of manure into soil would reduce the direct N_2O emissions and ammonia volatilization (Dalal *et al.*, 2003).
- Tailor fertilizer to local conditions – It might be possible to develop fertilizer types that are more suitable to specific local conditions and/or adjust application rates to take into account of soil characteristics, soil moisture content, and ambient and soil temperature (IEA, 2000).
- Cover crops – Winter or fallow cover crops can prevent the build-up of residual soil nitrogen, catching nitrogen that would otherwise be emitted as N_2O or leached (Cole *et al.*, 1997; Kroeze & Mosier, 2000; Bates, 2001).
- Improvement of fertilizer spreading – With better spreader maintenance, more uniform spreading can be achieved to increase efficiency and avoid over-application or under application (Worrell, 1994; DeAngelo *et al.*, 2006). Maintaining a fertilizer zone on the edge of fields to prevent losses into ditches at the side of fields would reduce fertilizer loss. Optimization of fertilizer distribution geometry can also prevent losses into ditches (Worrell, 1994). Fertilizer banding can increase efficiency of nitrogen use, reduce volatilization up to 35%, and increase yield up to 15% (Cole *et al.*, 1997; Kroeze and Mosier, 2000). In the band-mode application of easily soluble fertilizer, which was locally put into depth of 10 cm below vegetation, the N_2O emission rate was greatly reduced in comparison with that in broadcasting application (Tsuruta & Aliyama, 2000). Use of precision farming technologies such as yield mapping, global positioning system, and automatic sensing allows crop performance and output to be measured in different areas of a specific field and has potential in reducing nitrogen application and the N_2O emissions (Bates, 2001). Avoiding nitrogen fertilization on urine spots, through precision fertilization, reduced N_2O emissions (Kasper *et al.*, 2002).
- Simple fertilization reduction – This option is to reduce nitrogen-based fertilizer from one-time baseline application of 10%, 20%, or 30% (USEPA, 2006b). However, using this option will have a risk of under-fertilization (DeAngelo *et al.*, 2006).
- Maintain plant residue on the production site – It will allow the nitrogen contained in the residue to be reused, thus reducing the requirement of synthetic fertilizer. It should directly reduce the N_2O production from fertilizer and eliminate the N_2O emission from burning of the plant residue (IEA, 2000).

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: May affect the yield of crops.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) "Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions", *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.
4. Branosky, E.; Greenhalgh, S. (2007) "Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.
5. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
6. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
7. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) "Global Estimates of Potential Mitigation of Greenhouse Gs Emissions by Agriculture", *Nutrient Cycle in Agroecosystems*, 52, 221-228.
8. Dalal, R. C.; Wang, W.; Robertson, G.P.; Parton, W. (2003) "Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: a Review", *Australian J. Soil Res.* 41, 165-195.
9. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
10. DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) "Methane and Nitrous Oxide Mitigation in Agriculture', *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climiate Policy Special Issue, pp. 89-108.
11. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
12. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
13. Graus, W., Harmelink, M. and Hendriks, C. (2004) "Marginal GHG-Abatement curves for agriculture", Ecofys, Utrecht, the Netherlands.
14. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.

15. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
16. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
17. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
18. Kasper, G.J.; Holshof, G.; van den Pol-van Dasselaar, A. (2002) “Reduction of N_2O Emission by Introduction of Precision Fertilization”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
19. Kowalenko, G. (1999) “Assessing Nitrous Oxide Emissions from Farming Practice”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
20. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
21. Lemke, H.; Janzen, H.; Rochette, P. (1999) “Processes of Nitrous Oxide Emissions from Canadian Agroecosystems”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
22. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
23. McTaggert, I. P.; Clayton, H.; Smith, K.A. (1994) “Nitrous Oxide Flux from Fertilized Grassland: Strategies for Reducing Emissions”, in Non-CO_2 Greenhouse Gases: Why and How to Control, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
24. Moritomi, H.; Mochida, I. (2000) “N_2O Emission Inventory and the Abatement Technologies in Japan”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
25. Mosier, A.R.; Duxbury, J.M.; Freney, J.R.; Heinemeyer, O.; Minami, K. (1998) “Assessing and Mitigating N_2O Emissions from Agricultural Soils”, *Climatic Change*, 40, 7-38.
26. O’Hara, P.; Freney, J.; Ulyatt (2003) “Abatement of Agricultural Non-carbon Dioxide Greenhouse Gas Emissions – A Study of Research Requirements”, a report prepared for the Ministry of Agriculture and Forestry, New Zealand.
27. Tsuruta, H.; Akiyama, H. (2000) “NO and NO_2 Emissions with Application of Different Types of Nitrogen Fertilizer”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
28. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
29. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
30. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).

31. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
32. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
33. Worrell, E. (1994) “Potentials for Improved Use of Industrial Energy and Materials”, Utrecht University, Faculteit Scheikunde, the Netherlands.
34. J. Dolfing, P.J. Kuikman, G.L. Velthof, K. Zwart. Effects of cover cropping on emissions of N_2O from Dutch soils.
35. Mosier, A.; Kroeze, C.; Nevison, C.; Oenema, O.; Seitzinger, S.; Cleempu., O. van (1998) Closing the global atmospheric N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle; OECD/IPCC/IEA Phase II Development of IPCC Guidelines for National Greenhouse Gas Inventories. *Nutrient Cycling in Agroecosystems 52 (1998) 225-248.*
36. Oenema, O.; Gebauer, G.; Rodriguez, M.; Sapek, A.; Jarvis, S.C.; CorrÃ, W.J.; Yamulki, S. (1998) Controlling nitrous oxide emissions from grassland livestock production systems, *Nutrient Cycling Agroecosyst. 52 (1998), 2/3: 141-149*
37. Oenema, O.; Velthof, G.L.; Yamulki, S.; Jarvis, S.C. (1997), Nitrous oxide emissions from grazed grassland. *Soil Use and Management 13 (1997) 288-295.*
38. Peter O'Hara, John Freney, and Marc Ulyatt (2003), “Report prepared for the Ministry of Agriculture and Forestry on behalf of the Governor”, Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P3045_283655, May2003.
39. Reducing Greenhouse Gas Emissions from Livestock Agriculture in Manitoba, MANITOBA CLIMATE CHANGE TASK FORCE by Dr. Karin Wittenberg Head, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2 and Dinah Boadi, Research Associate, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-05.htm
40. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
41. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Agriculture/Agricultural Soil Management

Technology: Inhibition of nitrous oxide formation (B.1.1.2)

Description of the Technology:
Several agricultural activities increase mineral nitrogen availability in soils for nitrification and denitrification and ultimately increase the amount of N_2O emissions (USEPA, 2006a). Although most of the N_2O emissions from agricultural activities are from soils, the emission flux of N_2O per unit surface area of soil is small and varies greatly across time and space. The flux rate depends significantly on soil type, climate conditions, and soil management practices (IEA, 2000). Basically, there are two types of strategies and related technological options that are applicable to emission reduction of N_2O from agricultural soils. The first type uses measures that improve efficiencies in nitrogen utilization, and the second type inhibits the formation of nitrous oxide (Kowalenko, 1999). It should be noted that there are overlaps in these two types. For example, the use of the nitrification inhibitor and change in irrigation practices are also measures for improving nitrogen fertilizer efficiencies in the field.

With regards to inhibition of N_2O formation to reduce its emission from agricultural soil, there are many technological options and practices mentioned in the literature; but most of them were mentioned without detailed discussion and information. Below are a list and a brief description of the technological options and practices found from the literature search:

- Nitrification inhibitors – Nitrogen applied must be nitrified to nitrate before it is available for denitrification. Nitrification inhibitors delay the transformation of ammonium to nitrate (Cole *et al.*, 1997; Kroeze and Mosier, 2000). They can reduce the loss of nitrogen and permit crop production at constant or improved yields at given fertilizer application rates. The abatement cost for the nitrification inhibitor option is approximately $\$70/MT_{CO2\text{-}Eq.}$ (Gale and Freund, 2002).
- Urease inhibitors – Urease inhibitors delay the transformation of urea to ammonium to help matching the timing of nitrogen supply with crop demand (Cole *et al.*, 1997; Kroeze and Mosier, 2000).
- Alternative tillage systems – Some studies suggested that N_2O emissions could decline as a result of reduced nitrogen application rates following a shift to no till agriculture (Lemke *et al.*, 1999). Conversion from conventional tillage to no till will cause less disturbance to soils and more crop residual is retained (USEPA, 2006b)
- Changes in irrigation practices – Because soil-water content is an important factor in volatilization as well as nitrification/denitrification, irrigation practices can have an important impact on N_2O emissions from agriculture (Lemke *et al.*, 1999). However, the appropriate use of irrigation water is site-, crop-, soil-, and temperature-specific, therefore this option may not be easy for practical application.
- Improving drainage and avoiding soil compaction – Improving drainage and preventing soil compaction can reduce N_2O emission by 3% (Branosky & Greenhalgh, 2007; O’Hara *et al.*, 2003).

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: May affect the yield of crops.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.
3. Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) “Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions”, *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.
4. Branosky, E.; Greenhalgh, S. (2007) “Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.
5. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
6. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
7. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) “Global Estimates of Potential Mitigation of Greenhouse Gs Emissions by Agriculture”, *Nutrient Cycle in Agroecosystems*, 52, 221-228.
8. Dalal, R. C.; Wang, W.; Robertson, G.P.; Parton, W. (2003) “Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: a Review”, *Australian J. Soil Res.* 41, 165-195.
9. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
10. DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) “Methane and Nitrous Oxide Mitigation in Agriculture’, *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climiate Policy Special Issue, pp. 89-108.
11. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
12. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.

13. Graus, W., Harmelink, M. and Hendriks, C. (2004) "Marginal GHG-Abatement curves for agriculture", Ecofys, Utrecht, the Netherlands.
14. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
15. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
16. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
17. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
18. Kasper, G.J.; Holshof, G.; van den Pol-van Dasselaar, A. (2002) "Reduction of N_2O Emission by Introduction of Precision Fertilization", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
19. Kowalenko, G. (1999) "Assessing Nitrous Oxide Emissions from Farming Practice", *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
20. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
21. Lemke, H.; Janzen, H.; Rochette, P. (1999) "Processes of Nitrous Oxide Emissions from Canadian Agroecosystems", *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
22. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
23. McTaggert, I. P.; Clayton, H.; Smith, K.A. (1994) "Nitrous Oxide Flux from Fertilized Grassland: Strategies for Reducing Emissions", in Non-CO_2 Greenhouse Gases: Why and How to Control, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
24. Moritomi, H.; Mochida, I. (2000) "N_2O Emission Inventory and the Abatement Technologies in Japan", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
25. Mosier, A.R.; Duxbury, J.M.; Freney, J.R.; Heinemeyer, O.; Minami, K. (1998) "Assessing and Mitigating N_2O Emissions from Agricultural Soils", *Climatic Change*, 40, 7-38.
26. O'Hara, P.; Freney, J.; Ulyatt (2003) "Abatement of Agricultural Non-carbon Dioxide Greenhouse Gas Emissions – A Study of Research Requirements", a report prepared for the Ministry of Agriculture and Forestry, New Zealand.
27. Tsuruta, H.; Akiyama, H. (2000) "NO and NO_2 Emissions with Application of Different Types of Nitrogen Fertilizer", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
28. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

29. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
30. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
31. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
32. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
33. Worrell, E. (1994) “Potentials for Improved Use of Industrial Energy and Materials”, Utrecht University, Faculteit Scheikunde, the Netherlands.
34. J. Dolfing, P.J. Kuikman, G.L. Velthof, K. Zwart. Effects of cover cropping on emissions of N_2O from Dutch soils.
35. Mosier, A.; Kroeze, C.; Nevison, C.; Oenema, O.; Seitzinger, S.; Cleempu., O. van (1998) Closing the global atmospheric N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle; OECD/IPCC/IEA Phase II Development of IPCC Guidelines for National Greenhouse Gas Inventories. *Nutrient Cycling in Agroecosystems 52 (1998) 225-248.*
36. Oenema, O.; Gebauer, G.; Rodriguez, M.; Sapek, A.; Jarvis, S.C.; CorrÃ, W.J.; Yamulki, S. (1998) Controlling nitrous oxide emissions from grassland livestock production systems, *Nutrient Cycling Agroecosyst. 52 (1998), 2/3: 141-149*
37. Oenema, O.; Velthof, G.L.; Yamulki, S.; Jarvis, S.C. (1997), Nitrous oxide emissions from grazed grassland. *Soil Use and Management 13 (1997) 288-295.*
38. Peter O'Hara, John Freney, and Marc Ulyatt (2003), “Report prepared for the Ministry of Agriculture and Forestry on behalf of the Governor”, Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P3045_283655, May2003.
39. Reducing Greenhouse Gas Emissions from Livestock Agriculture in Manitoba, MANITOBA CLIMATE CHANGE TASK FORCE by Dr. Karin Wittenberg Head, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2 and Dinah Boadi, Research Associate, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-05.htm
40. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
41. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Agriculture/Manure Management

Technology: Options for emission reduction related to manure management (B.1.2)

Description of the Technology:
Livestock manure can produce N_2O emissions, as part of the nitrogen cycle through nitrification and denitrification of organic nitrogen compounds in manure and urine. With regards to reducing N_2O emission from manure management systems, there are several technological options and practices mentioned in the literature. Below are a list and a brief description of the technological options and practices found from the literature search:

- Optimizing the crude protein/energy ratio in animal diets – Some exploratory work has been performed on altering quantity of nitrogen excreted by domestic livestock by changing feed in such a way as to reducing nitrogen intake (Bates, 2001; IEA, 2000). One approach is to feed high quality diets which are low in protein. In one experiment it was found that the reduction in urinary nitrogen was 24% (O'Hara *et al.*, 2003). An attractive forage for cattle in this respect is corn silage, which reduces nitrogen intake, but improves utilization of the ingested nitrogen (de Jager *et al.*, 2001). Dairy cows fed with grasses high in water-soluble carbohydrate excreted 24% less nitrogen than those with normal diets (O'Hara *et al.*, 2003). Reduction of nitrogen output by pigs can be achieved by matching dietary protein concentration to physiological requirement. Other options include reduction of protein content, improvement of amino acid profile by amino acid supplementation, breeding and gene technology, and the use of feed additives (de Jager *et al.*, 2001).
- Nitrification and urease inhibitors – Nitrification and urease inhibitors can be used to reduce N_2O emissions from livestock manure. This option appears to be rather expensive (IEA, 2000).
- Waste storage – A shift towards anaerobic storage rather than aerobic storage of manures may reduce N_2O losses by a factor of 10 (Cole *et al.*, 1997; Kroeze and Mosier, 2000). However, it may also increase methane emission by a factor of 10, unless measures to capture and destroy methane are implemented (Bates, 2001).
- Use of cattle feed-pads during winter months – By keeping cattle on feed-pads during autumn/winter period, excretes can be collected and utilized as fertilizer later (Branosky & Greenhalgh, 2007; O'Hara *et al.*, 2003).
- Reducing the number of animals by increasing their productivity (Lucas *et al.*, 2006)
- Optimizing manure management and limiting grazing (Lucas *et al.*, 2006)

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: Some options may affect the yield of livestock.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) "Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions", *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.
4. Branosky, E.; Greenhalgh, S. (2007) "Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.
5. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
6. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
7. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) "Global Estimates of Potential Mitigation of Greenhouse Gs Emissions by Agriculture", *Nutrient Cycle in Agroecosystems*, 52, 221-228.
8. Dalal, R. C.; Wang, W.; Robertson, G.P.; Parton, W. (2003) "Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: a Review", *Australian J. Soil Res.* 41, 165-195.
9. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
10. DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) "Methane and Nitrous Oxide Mitigation in Agriculture', *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climiate Policy Special Issue, pp. 89-108.
11. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
12. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
13. Graus, W., Harmelink, M. and Hendriks, C. (2004) "Marginal GHG-Abatement curves for agriculture", Ecofys, Utrecht, the Netherlands.
14. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
15. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.

16. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
17. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
18. Kasper, G.J.; Holshof, G.; van den Pol-van Dasselaar, A. (2002) “Reduction of N_2O Emission by Introduction of Precision Fertilization”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
19. Kowalenko, G. (1999) “Assessing Nitrous Oxide Emissions from Farming Practice”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
20. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
21. Lemke, H.; Janzen, H.; Rochette, P. (1999) “Processes of Nitrous Oxide Emissions from Canadian Agroecosystems”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
22. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
23. McTaggert, I. P.; Clayton, H.; Smith, K.A. (1994) “Nitrous Oxide Flux from Fertilized Grassland: Strategies for Reducing Emissions”, in Non-CO_2 Greenhouse Gases: Why and How to Control, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
24. Moritomi, H.; Mochida, I. (2000) “N_2O Emission Inventory and the Abatement Technologies in Japan”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
25. Mosier, A.R.; Duxbury, J.M.; Freney, J.R.; Heinemeyer, O.; Minami, K. (1998) “Assessing and Mitigating N_2O Emissions from Agricultural Soils”, *Climatic Change*, 40, 7-38.
26. O’Hara, P.; Freney, J.; Ulyatt (2003) “Abatement of Agricultural Non-carbon Dioxide Greenhouse Gas Emissions – A Study of Research Requirements”, a report prepared for the Ministry of Agriculture and Forestry, New Zealand.
27. Tsuruta, H.; Akiyama, H. (2000) “NO and NO_2 Emissions with Application of Different Types of Nitrogen Fertilizer”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
28. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
29. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
30. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
31. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.

32. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
33. Worrell, E. (1994) “Potentials for Improved Use of Industrial Energy and Materials”, Utrecht University, Faculteit Scheikunde, the Netherlands.
34. J. Dolfing, P.J. Kuikman, G.L. Velthof, K. Zwart. Effects of cover cropping on emissions of N_2O from Dutch soils.
35. Mosier, A.; Kroeze, C.; Nevison, C.; Oenema, O.; Seitzinger, S.; Cleempu., O. van (1998) Closing the global atmospheric N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle; OECD/IPCC/IEA Phase II Development of IPCC Guidelines for National Greenhouse Gas Inventories. *Nutrient Cycling in Agroecosystems 52 (1998) 225-248.*
36. Oenema, O.; Gebauer, G.; Rodriguez, M.; Sapek, A.; Jarvis, S.C.; CorrÃ, W.J.; Yamulki, S. (1998) Controlling nitrous oxide emissions from grassland livestock production systems, *Nutrient Cycling Agroecosyst. 52 (1998), 2/3: 141-149*
37. Oenema, O.; Velthof, G.L.; Yamulki, S.; Jarvis, S.C. (1997), Nitrous oxide emissions from grazed grassland. *Soil Use and Management 13 (1997) 288-295.*
38. Peter O'Hara, John Freney, and Marc Ulyatt (2003), “Report prepared for the Ministry of Agriculture and Forestry on behalf of the Governor”, Ministerial Group on Climate Change, the Minister of Agriculture and the Primary Industries Council, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-19.htm#P3045_283655, May2003.
39. Reducing Greenhouse Gas Emissions from Livestock Agriculture in Manitoba, MANITOBA CLIMATE CHANGE TASK FORCE by Dr. Karin Wittenberg Head, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2 and Dinah Boadi, Research Associate, Department of Animal Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/abatement-of-agricultural-greenhouse-gas-emissions/abatement-of-agricultural-greenhouse-gas-emissions-05.htm
40. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
41. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Agriculture/Field Burning of Agricultural Residues

Technology: Options for emission reduction related to burning of agricultural residues (B.1.3)

Description of the Technology:
Large quantities of agricultural crop residues are produced from farming activitiesCrop residue burning is a net source of nitrous oxide, which is released during combustion (USEPA, 2006a). The mitigation options for reducing N_2O emissions from agricultural residue include improved fire management practices, plowing under, or composting (Gale & Freund, 2002).

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: None reported.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Beach, R.H.; DeAngelo, B.J.; Rose, S.; Li, C.; Salas, W.; DelGrosso, S.J. (2006) "Mitigation Potential and Costs for Global Agricultural Greenhouse Gas Emissions", *Proc. International Association of Agricultural Economists Conference*, Gold Coast, Australia, August 12-18.
3. Branosky, E.; Greenhalgh, S. (2007) "Agriculture and Climate Change: Greenhouse Gas Mitigation Opportunities and the 2007 Farm Bill, Water Resource Institute, Washington, D.C., March 2007.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. Cole, C.V.; Duxbury, J.; Freney, J.; Heinemeyer, O.; Mosier, A.; Paustian, K.; Rosenberg, M.; Sampson, N.; Sauerbeck, D.; Zhao, Q. (1997) "Global Estimates of Potential Mitigation of Greenhouse Gs Emissions by Agriculture", *Nutrient Cycle in Agroecosystems*, 52, 221-228.
6. Dalal, R. C.; Wang, W.; Robertson, G.P.; Parton, W. (2003) "Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: a Review", *Australian J. Soil Res.* 41, 165-195.
7. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.

8. DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) “Methane and Nitrous Oxide Mitigation in Agriculture’, *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climiate Policy Special Issue, pp. 89-108.
9. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Graus, W., Harmelink, M. and Hendriks, C. (2004) “Marginal GHG-Abatement curves for agriculture”, Ecofys, Utrecht, the Netherlands.
12. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
13. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
14. Lemke, H.; Janzen, H.; Rochette, P. (1999) “Processes of Nitrous Oxide Emissions from Canadian Agroecosystems”, *Proc. International Workshop on Reducing Nitrous Oxide Emissions from Agroecosytems*, Banff, Alberta, March 1999.
15. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
16. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
17. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
18. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
19. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
20. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
21. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
22. U.S. Environmental Protection Agency (1999) “Report on U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions”, United States Environmental Protection Agency, EPA 430-R-99-013, September 1999.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Energy/Mobile Combustion

Technology: Options for emission reduction related to mobile combustion (B.2.1)

Description of the Technology:
In the mobile combustion sector, N_2O is emitted as a by-product of fuel combustion (USEPA, 2006a). The degree to which N_2O emissions have increased (or decreased) from mobile sources depends upon factors such as driving practices (i.e., number of cold starts) and size, type, and age of the catalyst. The production of N_2O emissions can increase up to a factor of 10 to 16 due to aging of the catalyst (de Jager *et al.*, 2001). N_2O emissions from mobile sources for areas with a high number of road vehicles with emission controls, therefore, can be substantial (USEPA, 2006a). The technological options for reducing N_2O emission from mobile sources include the following:

- Improve catalyst performance – In most of the existing catalytic converters, N_2O is produced as a result of an incomplete reduction of NO_x to NO. In the longer term it might be possible to develop a new type of catalytic converter that will also prevent N_2O formation. However, this would require a significant R&D effort (de Jager *et al.*, 2001). N_2O emissions increase with the age of the catalyst in the converter. Although increased rate of replacement of catalytic converters will reduce N_2O emission, it is not a realistic measure because the cost would be prohibitively high (de Jager *et al.*, 2001). The catalyst performance can also be improved by having electrically heated catalyst, optimal positioning of the catalyst for accelerated heating, and catalytic insulation to keep catalytic converters hot for up to 24 hours. These technologies are already developed and mainly aim at reducing start-up emissions of NO_x and VOCs, little or no attention has been paid in the development and testing with regards to emission reduction of N_2O (de Jager *et al.*, 2001).
- Use of N_2O-decomposition catalyst – A future catalytic converter may consist of a traditional three-way catalyst (for NO_x CO and VOC), followed by a N_2O-decomposition catalyst. But there are technical obstacles to overcome. At this point, it is doubtful that the problems can be solved in the next few decades (de Jager *et al.*, 2001; US Climate Change, 2005).
- Use of alternative technologies for NO_x-emission reduction – Use of the three-way catalysts is not the sole option for reducing NO_x emissions. Increased use of low-VOC and low-NO_x engines may replace the traditional three-way catalyst controlled engines. Consequently, N_2O emissions from three-way catalysts can be avoided (de Jager *et al.*, 2001).
- Alternative fuel – Technological breakthroughs, such as fuel cell, will also greatly reduce the level of NO_x emissions (Lucas *et al.*, 2006). Fuel substitutes, such as use of hybrid, electric, ethanol, and natural gas vehicles, will also reduce N_2O emissions.

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: Most of these technological options are still in the development stage.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.
4. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
5. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
6. de Soate, G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control”, in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
7. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
8. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
9. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
10. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
11. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
12. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
13. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
14. Moritomi, H.; Mochida, I. (2000) “N_2O Emission Inventory and the Abatement Technologies in Japan”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
15. Oonk, J. (1995) “Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control”, Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.

16. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
17. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
18. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
19. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
20. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Energy/Stationary Combustion

Technology: Options for emission reduction related to stationary combustion (B.2.2)

Description of the Technology:
Stationary combustion includes all the combustion activities except waste incineration, transportation (mobile combustion), and biomass burning for non-energy purposes. For stationary sources, nitrous oxide may result from the incomplete combustion of fuels (USEPA, 2006a).

Emission concentrations of N_2O from burning of fossil fuels in stationary combustion processes are low, typically 1 to 2 ppmV for coal-fired plants and 1 ppmV or less for oil- and gas-fired plants. Sources with higher emission concentrations are flue gases from fluidized bed combustion (FBC), flue gases from the selective non-catalytic reduction (SNCR) process, and combustion of wood, waste, and other biomass (de Jager *et al.*, 2001). Technological options for emission reduction of N_2O may be categorized into three groups: (1) reduced emissions from fluidized bed combustion; (2) use of selective catalytic reduction; and (3) fuel shift and reduction in fossil fuel consumption (de Jager *et al.*, 2001; de Soate, 1993; EC, 2001).

- Fluidized bed combustion (FBC) – Fluidized bed combustion has a higher energy conversion than conventional pulverized fuel combustion, and it has lower NO_x emissions due to a lower combustion temperature. However, the lower combustion temperature, between 800 and 900 ^oC, leads to higher N_2O emission concentrations, in the range of 30-150 ppmV. Several technological measures to reduce N_2O emissions are potentially available: (1) optimizing operating conditions, (2) using reversed air staging, (3) use of afterburner, (4) use of catalytic reduction, and (5) use of pressurized fluidized bed (de Jager *et al.*, 2001; IEA, 2000). It was estimated in an EU report, for applications of these technologies at FBC facilities, the cost is approximately \$59/$MT_{CO2\text{-}Eq.}$ for installing the gas afterburner, \$51/$MT_{CO2\text{-}Eq.}$ for reverse air staging, and \$170/$MT_{CO2\text{-}Eq.}$ for "optimized" operating conditions coupled with the use of catalytic control (IEA, 2000). It should be noted that these cost estimates were based on a very limited set of studies.
- Use of selective catalytic reduction – Use of selective non-catalytic reduction (SNCR) for reducing NO_x emissions requires higher operating temperatures, but it also creates N_2O emissions. An alternative NO_x abatement system may be selective catalytic reduction (SCR), which is considered preferable with regards to N_2O emission reduction; however, the specific cost of NO_x abatement of SCR is twice as expensive than the cost of SNCR (de Jager *et al.*, 2001). It should be noted here that some consider SCR effective in reduction of N_2O emissions while the others hold an opposite view (USEPA 2006a; Smit *et al.*, 2001)
- Fuel shift and reduction of fuel consumption – A shift from coal to oil or gas would result in lower N_2O emissions from fuel combustion. Reduction in fossil fuel consumption can be achieved, for example, by applying energy-efficiency improvement measures, applying energy saving measures, and increasing use of renewable energy. A shift to non-fossil energy source will further reduce the emissions. However, it is very unlikely that these options will be implemented as part of a N_2O abatement option (de Jager *et al.*, 2001; IEA, 2000).

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: Most of these technological options are still in the development stage.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. de Soate, G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control", in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
6. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
7. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
8. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
9. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
10. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
11. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
12. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
13. Moritomi, H.; Mochida, I. (2000) "N_2O Emission Inventory and the Abatement Technologies in Japan", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.

14. Oonk, J. (1995) “Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control”, Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.
15. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
16. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
17. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
18. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
19. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO$_2$ Greenhouse Gases: Nitrous Oxide

Source/Sectors: Energy/Municipal Solid Waste Combustion

Technology: Options for emission reduction related to MSW combustion (B.2.3)

Description of the Technology:
About 7 to 17% of the municipal solid wastes (MSW) in the United States are managed by combustion. Almost all combustion of MSW occurs at waste-to-energy facilities where energy is recovered, while N_2O is a by-product of the combustion process (USEPA, 2006a). Nitrous oxide emissions from this sector depend on a variety of factors, including types of waste as well as combustion temperature. Overall, waste incineration is a relatively minor source of N_2O emission. The emission from this sector can be effectively reduced from source reduction, reuse, and recycling of municipal solid waste (IEA, 2000).

Effectiveness: Low

Implementability: Low

Reliability: Low

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: Low

Industry Acceptance Level: Low

Limitations: Most of these technological options are still in the development stage.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO$_2$ Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO$_2$ Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. de Soate, G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control”, in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
6. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)

7. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
8. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
9. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
10. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
11. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
12. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
13. Moritomi, H.; Mochida, I. (2000) “N_2O Emission Inventory and the Abatement Technologies in Japan”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
14. Oonk, J. (1995) “Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control”, Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.
15. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
16. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
17. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
18. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
19. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO$_2$ Greenhouse Gases: Nitrous Oxide

Source/Sectors: Industrial Processes/Nitric Acid Production

Technology: High-temperature catalytic reduction (B.3.1.1)

Description of the Technology:
Nitric acid (HNO_3) is used in production of synthetic fertilizers, adipic acid, and explosives. Virtually all of the nitric acid production in the United States is manufactured by the catalytic oxidation of ammonia. During this reaction, N_2O is formed as a by-product and is released from reactor and vented into the atmosphere (USEPA, 2006b).

N_2O concentrations in flue gases of nitric acid plants typically range from 300 to 1,700 ppmV. This range is generally more suitable for catalytic conversion than for direct incineration because of less energy input (de Jager *et al.*, 2001). This abatement option has several variations developed by different companies, such as BASF, Grand Paroisse, Norsk Hydro, and HITK, all involving the decomposition of N_2O into nitrogen and oxygen using various catalysts. The average estimated reduction efficiency is approximately 90% (USEPA, 2006b; IEA, 2000 & 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
High-temp catalytic reduction (BASF)[1]	10	-	80	100	\$2.76	\$0.17	\$0.00
High-temp catalytic reduction (Grand Paroisse)[1]	10	-	77.6	100	\$3.09	\$0.16	\$0.00
High-temp catalytic reduction (HITK)[1]	10	-	100	100	\$3.18	\$0.22	\$0.00
High-temp catalytic reduction (Norsk Hydro)[1]	10	-	90	100	\$2.32	\$0.15	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}Eq.}$
1: IEA (2000); IEA (2003); USEPA (2004)

Industry Acceptance Level: Good

Limitations: They are presently still in experimental and R&D stages.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.
7. de Soate, G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control”, in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
8. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
9. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
12. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
13. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
14. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
15. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
16. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
17. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.

18. Oonk, J. (1995) “Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control”, Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.
19. Smit, A.W.; Gent, M.M.C.; van den Brink, R.W. (2001) “Market Analysis DeN_2O: Market Potential for Reduction of N_2O Emissions at Nitric Acid Facilities”, Leiden, Netherlands: Jacobs Engineering Nederland.
20. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
21. U.S. Environmental Protection Agency (2001) “U.S. Adipic Acid and Nitric Acid N_2O Emissions 1990 – 2020: Inventories, Projections and Opportunities for Reductions (draft)” Office of Atmospheric Programs, United States Environmental Protection Agency, November, 2001.
22. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
23. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
24. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
25. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Industrial Processes/Nitric Acid Production

Technology: Low-temperature catalytic reduction (B.3.1.2)

Description of the Technology:
Nitric acid (HNO_3) is used in production of synthetic fertilizers, adipic acid, and explosives. Virtually all of the nitric acid production in the United States is manufactured by the catalytic oxidation of ammonia. During this reaction, N_2O is formed as a by-product and is released from reactor and vented into the atmosphere (USEPA, 2006b).

Low-temperature catalytic reduction systems work similarly to high-temperature counterparts, but they do not require additional heat to decompose N_2O. Some versions of this abatement require propane addition to the gas stream before undergoing the reaction process. The average estimated reduction efficiency is approximately 95% (USEPA, 2006b; IEA, 2000 & 2003).

Effectiveness: Good

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Low-temp catalytic reduction with propane addition[1]	10	-	95	100	\$3.64	\$1.81	\$0.00
Low-temp catalytic reduction (Krupp Uhde)[1]	10	-	95	100	\$3.45	\$0.20	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2000); IEA (2003); USEPA (2004)

Industry Acceptance Level: Good

Limitations: They are presently still in experimental and R&D stages

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.

3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
7. de Soate, G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control", in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
8. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
9. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
12. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
13. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
14. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
15. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
16. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
17. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
18. Oonk, J. (1995) "Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control", Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.

19. Smit, A.W.; Gent, M.M.C.; van den Brink, R.W. (2001) "Market Analysis DeN_2O: Market Potential for Reduction of N_2O Emissions at Nitric Acid Facilities", Leiden, Netherlands: Jacobs Engineering Nederland.
20. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
21. U.S. Environmental Protection Agency (2001) "U.S. Adipic Acid and Nitric Acid N_2O Emissions 1990 – 2020: Inventories, Projections and Opportunities for Reductions (draft)" Office of Atmospheric Programs, United States Environmental Protection Agency, November, 2001.
22. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
23. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
24. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
25. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Industrial Processes/Nitric Acid Production

Technology: Non-selective catalytic reduction (B.3.1.3)

Description of the Technology:
Nitric acid (HNO_3) is used in production of synthetic fertilizers, adipic acid, and explosives. Virtually all of the nitric acid production in the United States is manufactured by the catalytic oxidation of ammonia. During this reaction, N_2O is formed as a by-product and is released from reactor and vented into the atmosphere (USEPA, 2006b).

Non-selective catalytic reduction (NSCR) uses a fuel and a catalyst to consume free oxygen in the tail gas and to convert NO_x to elemental nitrogen. Since all oxygen must be consumed before NO_x is reduced, excess fuel must be used and result in methane emissions. NSCR can reduce N_2O emission by 80-90 percent (USEPA, 2006b; IEA, 2000 & 2003).

Effectiveness: Good

Implementability: Good

Reliability: Good

Maturity: Good

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Non-selective catalytic reduction[1]	20	-	85	100	$6.29	$0.16	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{CO2-Eq.}$
1: IEA (2000); IEA (2003); USEPA (2004)

Industry Acceptance Level: Good

Limitations: None reported.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.

5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
7. de Soate, G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control", in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
8. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
9. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
12. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
13. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
14. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
15. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
16. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
17. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
18. Oonk, J. (1995) "Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control", Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.
19. Smit, A.W.; Gent, M.M.C.; van den Brink, R.W. (2001) "Market Analysis DeN_2O: Market Potential for Reduction of N_2O Emissions at Nitric Acid Facilities", Leiden, Netherlands: Jacobs Engineering Nederland.
20. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

21. U.S. Environmental Protection Agency (2001) "U.S. Adipic Acid and Nitric Acid N_2O Emissions 1990 – 2020: Inventories, Projections and Opportunities for Reductions (draft)" Office of Atmospheric Programs, United States Environmental Protection Agency, November, 2001.
22. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
23. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
24. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
25. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Industrial Processes/Nitric Acid Production

Technology: Options other than catalytic reduction (B.3.1.4)

Description of the Technology:
Nitric acid (HNO_3) is used in production of synthetic fertilizers, adipic acid, and explosives. Virtually all of the nitric acid production in the United States is manufactured by the catalytic oxidation of ammonia. During this reaction, N_2O is formed as a by-product and is released from reactor and vented into the atmosphere (USEPA, 2006b).

There are other technological options for nitrous oxide emission reduction, they include:

- Thermal decomposition – Direct thermal decomposition (afterburning) with fuel injection of natural gas or methane is generally not considered as a feasible option because of the relatively low off-gas concentrations of N_2O from nitric acid production. However, in some cases off-gases could be mixed with high-temperature off-gases of other near-by industrial processes, and it could result in a net reduction of N_2O. Reduction potential and costs are site-specific and not quantified in the literature (de Jager *et al.*, 2001).
- Photo-catalytic conversion – It was reported in 1920s that absorption of ultraviolet light of 158 or 185 nm would result in the dissociation of N_2O (Oonk, 1995). Neither reduction potential nor costs have been developed and research on its applicability to off-gases of nitric acid production is required (de Jager *et al.*, 2001).
- Biofiltration of off-gases using denitrifying bacteria – Nitrous oxide might be decomposed biologically. In this option, the N_2O is dissolved into water and subsequently converted to nitrogen and oxygen gases by denitrifying bacteria (Oonk, 1995). Neither reduction potential nor costs have been developed and research on its applicability to off-gases of nitric acid production is required (de Jager *et al.*, 2001).

Effectiveness: Fair

Implementability: Fair

Reliability: Fair

Maturity: Fair

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: None reported.

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.

2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
7. de Soate, G. (1993) "Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control", in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
8. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
9. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
12. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
13. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
14. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
15. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
16. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
17. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
18. Oonk, J. (1995) "Nitrous Oxide from Stationary Combustion and Industry – Emissions and Options for Control", Netherlands Organization for Applied Scientific Research, Apeldoorn, the Netherlands.

19. Smit, A.W.; Gent, M.M.C.; van den Brink, R.W. (2001) "Market Analysis DeN_2O: Market Potential for Reduction of N_2O Emissions at Nitric Acid Facilities", Leiden, Netherlands: Jacobs Engineering Nederland.
20. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
21. U.S. Environmental Protection Agency (2001) "U.S. Adipic Acid and Nitric Acid N_2O Emissions 1990 – 2020: Inventories, Projections and Opportunities for Reductions (draft)" Office of Atmospheric Programs, United States Environmental Protection Agency, November, 2001.
22. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
23. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
24. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
25. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Solvent and Other Product Uses

Technology: Options to reduce nitrous oxide emissions from solvent and other product uses (B.4)

Description of the Technology:
Nitrous oxide is often used with oxygen in carrier gases to administer more potent inhalation anesthetics for general anesthesia and as an anesthetic in various dental and veterinary applications. It is also commonly used as a propellant in pressure and aerosol products with pressure-packaged whipped cream as the largest application.

Nitrous oxide emissions from this sector are not included in the recent California GHG inventory report by CEC (CEC, 2006). No practical technological options for reducing nitrous oxide emissions from this sector were found from the literature search.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: Not applicable

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. Bates, J. (2001) “Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis”, A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) “Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies”, *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) “Emission Reduction of Non-CO_2 Greenhouse Gases”, Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) “Cost-effective Reduction of Non-CO_2 Greenhouse Gases”, Energy Policy 29, 1325-1331.

7. de Soate, G. (1993) “Nitrous Oxide from Combustion and Industry: Chemistry, emissions, and Control”, in *Proc. of International Workshop Methane and Nitrous Oxide: Methods in National Emissions Inventories and Options for Control*, Amersfoort, the Netherlands, February 3-5.
8. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) “Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry” *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
9. European Commission (2001) “Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change”, Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
10. Gale, J.J.; Freund, P. (2002) “An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
11. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) “Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15”, ECOFYS Interim Report, Utrech, the Netherlands.
12. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) “Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life”, J. Chem. Eng. of Japan, 36(4), 449-457.
13. International Energy Agency (2000) “Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide”, Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
14. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
15. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
16. Kroeze, C.; Mosier, A.R. (2000) “New Estimates for Emissions of Nitrous Oxide”, in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
17. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) “Long-term Reduction Potential of Non-CO_2 Greenhouse Gases”, Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
18. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
19. U.S. Environmental Protection Agency (2003) “International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21”, a report prepared by ICF Consulting for the United States Environmental Protection Agency.
20. U.S. Environmental Protection Agency (2004) “International Methane and Nitrous Oxide Emissions and Mitigation Data”, United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
21. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
22. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Land-use Changes and Forestry

Technology: Options to reduce nitrous oxide emissions from land-use changes and forestry (B.5)

Description of the Technology:
In California there are three relevant emission sources in the sector of land-use changes and forestry: (1) forestland remaining forestland, (2) settlement remaining settlement, and (3) forest fires.

Nitrous oxide emissions from these three sub-sectors are not included in the recent California GHG inventory report by CEC (CEC, 2006). No practical technological options for reducing nitrous oxide emissions from this sector were found from the literature search.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Environmental Benefits: Not applicable

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.
2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. de la Chesnaye, F.; Harvey, R.; Kruger, D.; Laitner, J.A. (2001) "Cost-effective Reduction of Non-CO_2 Greenhouse Gases", Energy Policy 29, 1325-1331.
7. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.

8. Hendriks, C.A.; de Jager, D.; Blok, K. (1998) "Emission Reduction Potential and Costs for Methane and Nitrous Oxide in the EU-15", ECOFYS Interim Report, Utrech, the Netherlands.
9. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
10. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
11. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
12. Kroeze, C.; Mosier, A.R. (2000) "New Estimates for Emissions of Nitrous Oxide", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation, edited by J. van Ham *et al.*, Kluwer Academic Publisher, Dordrecht, the Netherlands.
13. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
14. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
15. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
16. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
17. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
18. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: Nitrous Oxide

Source/Sectors: Waste

Technology: Options to reduce nitrous oxide emissions from the waste sector (B.6)

Description of the Technology:
Waste management is one of the minor sources of N_2O emissions. The emissions can come from domestic wastewater and industrial wastewater. Nitrogen compounds, such as urea, ammonia, and proteins, are converted to nitrate (NO_3^-) under aerobic nitrification. Denitrification occurs under anoxic conditions (absence of free oxygen, but presence of nitrate) and converts nitrate into nitrogen. Nitrification/denitrification (N/DN), which is to remove nitrogen compounds from wastewater, is required for many municipal wastewater treatments. Nitrous oxide is an intermediate product of both nitrification and denitrification processes, but is more often associated with denitrification (USEPA, 2006a).

In contrast to methane emission reduction technologies, which are primarily focused on untreated wastewater and on-site small wastewater treatment plants, N_2O reduction should be more focused on N_2O emission from denitrification in large-scale, centralized plant (de Jager *et al.*, 2001). Under optimal operating conditions, N_2O formation can be reduced by up to one-third during nitrification and two-thirds during denitrification (IEA, 2000). Although no cost figures have been reported, it is expected that process optimization can be accomplished with negligible costs (Hendriks *et al.*, 1998). It has also been reported that, from comparisons of N_2O emission from several wastewater treatment processes, intermittent aeration in the nitrification/denitrification process is optimal with regards to reduction of N_2O emissions as well as high nitrogen removal (Inamori *et al.*, 2003). When nitrogen removal in wastewater treatment is not necessary and the application of wastewater sludge to agricultural land as a nitrogen source is allowable, the net N_2O emission from wastewater sector may be reduced (de Jager *et al.*, 2001). Nitrous oxide is an intermediate by-product of decomposition of organic nitrogen compounds, such as protein and urea, in industrial wastewater. N_2O generation and emission mechanisms are not well understood (IEA, 2000). No specific technological options for emission reduction were found from the literature search.

Effectiveness: Fair

Implementability: Fair

Reliability: Fair

Maturity: Low

Environmental Benefits: It reduces nitrous oxide emission.

Cost Effectiveness: None reported.

Industry Acceptance Level: Low

Limitations: Nitrification/denitrification is required at many wastewater treatment plants.

Sources of Information:

1. Bates, J. (2001) "Economic Evaluation of Emission Reductions of Nitrous Oxide and Methane in Agriculture in the EU: Bottom-up Analysis", A final report to European Commission.

2. Blok, K.; de Jager, D. (1994) "Effectiveness of Non-CO_2 Greenhouse Gas Emission Reduction Technologies", *Environ. Monitoring & Assessment*, 31, 17-40.
3. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
5. de Jager, D.; Hendriks, C.A.; Byers, C. ; van Brummelen, M.; Petersdorff, C. ; Struker, A.H.M.; Blok, K.; Oonk, J ; Gerbens, S.; Zeeman, G. (2001) "Emission Reduction of Non-CO_2 Greenhouse Gases", Dutch National Research Programme on Global Air Pollution and Climate Change, Report no. 410-200-094.
6. Delhotal, K.G.; de la Chesnaye, F.C.; Gardinar, A.; Bates, J.; Sankovski, A. (2006) "Mitigation of Methane and Nitrous Oxide Emissions form Waste, Energy and Industry" *The Energy Journal*, Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, pp. 45-62.
7. European Commission (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change", Brussels. (Document can be found at http://ec.europa.eu/environment/enveco/climate_change/sectoral_objectives.htm)
8. Gale, J.J.; Freund, P. (2002) "An Assessment of the Costs and Global Impact of Nitrous Oxide Abatement Measures", in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control Options and Policy Aspects, edited by J. van Ham *et al.*, Millpress, Rotterdam, the Netherlands.
9. Inamori, Y.; Kimochi, Y.; Inamori, R.; Gui, P.; Kong, H.; Mizuochi, M. (2003) "Control of Anthropogenic CH_4 and N_2O Emissions from Several Industrial Sources and from Daily Human Life", J. Chem. Eng. of Japan, 36(4), 449-457.
10. International Energy Agency (2000) "Abatement of Emissions of Other Greenhouse Gases – Nitrous Oxide", Report Number PH3/29, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, September 2000.
11. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
12. Intergovernmental Panel on Climate Change (2000), Climate Change 2000 - The Third Assessment Report - Working Group 3, Final Draft, October 2000.
13. Lucas, P.L.; van Vuuren, D.P.; Jos Oliver, G.J.; den Elzen, M.G.J. (2006) "Long-term Reduction Potential of Non-CO_2 Greenhouse Gases", Netherlands Environment Assessment Agency (MNP), published on line November 28, 2006.
14. U.S. Environmental Protection Agency (2003) "International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21", a report prepared by ICF Consulting for the United States Environmental Protection Agency.
15. U.S. Environmental Protection Agency (2004) "International Methane and Nitrous Oxide Emissions and Mitigation Data", United States Environmental Protection Agency. Available online at www.wpa.gov/methane/appendices.html (in Excel file).
16. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006.
17. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

APPENDIX C

Technological Options for Emission Reduction of High-GWP Gases

- 1. - Substitution of Ozone Depleting Substances
  - 1.1 - Refrigeration and Air Conditioning
    - 1.1.1 - Household Refrigeration
      - 1.1.1.1 - Refrigerant recovery/recycling
      - 1.1.1.2 - Use of hydrocarbons
    - 1.1.2 - Residential Air-conditioners and Heat Pumps
      - 1.1.2.1 - Refrigerant recovery/recycling
      - 1.1.2.2 - Leak repair
    - 1.1.3 - Motor Vehicle Air Conditioners
      - 1.1.3.1 - Refrigerant recovery/recycling
      - 1.1.3.2 - Improved HFC-134a systems
      - 1.1.3.3 - HFC-152a systems
      - 1.1.3.4 - Use of CO_2
    - 1.1.4 - Chillers
    - 1.1.5 - Retail Food Refrigeration
      - 1.1.5.1 - Leak repair
      - 1.1.5.2 - Alternative systems
      - 1.1.5.3 - Ammonia secondary loop systems
      - 1.1.5.4 - HFC secondary loop systems
      - 1.1.5.5 - Replacing direct expansion systems with distributed systems
    - 1.1.6 - Cold Storage Warehouse
      - 1.1.6.1 - Leak repair
      - 1.1.6.2 - Alternative systems
      - 1.1.6.3 - Ammonia secondary loop systems
      - 1.1.6.4 - HFC secondary loop systems
      - 1.1.6.5 - Replacing direct expansion systems with distributed systems
    - 1.1.7 - Refrigerated Transport
    - 1.1.8 - Industrial Process Refrigeration
      - 1.1.8.1 - Leak repair
      - 1.1.8.2 - Alternative systems
      - 1.1.8.3 - Ammonia secondary loop systems
    - 1.1.9 - Commercial Unitary Air-conditioning
      - 1.1.9.1 - Refrigerant recovery/recycling
      - 1.1.9.2 - Leak repair
  - 1.2 - Technical Aerosols
    - 1.2.1 - End-uses of MDIs
    - 1.2.2 - End-uses of Consumer and Specialty Products
      - 1.2.2.1 - Substitution with lower GWP HFCs
      - 1.2.2.2 - VOC propellants
      - 1.2.2.3 - Not-in-kind (NIK) products
  - 1.3 - Solvents
    - 1.3.1 - Improved equipment and cleaning processes
    - 1.3.2 - Aqueous cleaning
    - 1.3.3 - Semi-aqueous cleaning
    - 1.3.4 - Alternative solvents

- 1.4 - Foams
  - 1.4.1 - Replace HFC-134a in appliance with hydrocarbons
  - 1.4.2 - Replace HFC-245fa in appliance with hydrocarbons
  - 1.4.3 - Replace HFC-245fa in sprays with hydrocarbons
  - 1.4.4 - Replace HFC-245fa in sprays with water-blown CO_2
  - 1.4.5 - Replace HFC-134a/152a in extruded polystyrene with water-blown CO_2
- 1.5 - Fire Fighting
  - 1.5.1 - Water mist systems
  - 1.5.2 - Inert gas systems
- 1.6 - Sterilization

2.- Electrical Transmission and Distribution
- 2.1 - Leakage reduction and recovery
- 2.2 - Improved SF_6 Recovery for switch gear manufacture

3.- Semiconductor Manufacture
- 3.1 - CVD cleaning emission reduction/NF_3 remote clean
- 3.2 - CVD cleaning emission reduction/C_3F_8 replacement
- 3.3 - Point-of-use plasma abatement
- 3.4 - Thermal destruction or processing units
- 3.5 - Catalytic decomposition system
- 3.6 - PFC recapture/recovery

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Household Refrigeration

Technology: Refrigerant recovery/recycling (C.1.1.1.1)

Description of the Technology:
Household refrigeration system typically consists of a hermetically-sealed circulation loop that contains the refrigerant and connects an evaporator, a condenser, and a compressor. Refrigerant loss occurs mainly due to mechanical damage of the evaporator coil (USEPA, 2001).

Practicing refrigerant recovery for reuse or destruction can significantly reduce HFCs emissions. Recovery options apply a refrigerant recovery device that transfers refrigerant into a storage container prior to servicing or disposing equipment. After the recovery process, the refrigerant contained in the storage container either is recharged back into the source equipment, cleaned through the use of recycling devices, purified for resale at a reclamation facilities, or disposed safely in an environmentally-safe manner (IEA, 2003, USEPA, 2001). These practices are already in baseline in many refrigeration systems because of the cost efficiency yielded by the reuse and re-sold processes; however, small equipments such as house refrigeration has less recoverable charges, thus being less cost effective. Yet, refrigerant recovery/recycling is believed to be the most feasible option to reduce HFC emissions (IEA, 2003).

Effectiveness: It can reduce total emissions by 95% (USEPA, 2001).

Implementability: Technically applicable in all regions.

Reliability: No risk and uncertainty associated with this option is recognized (IEA, 2003).

Maturity: Refrigerant recovery equipment is widely available and used extensively in developed countries. In some countries such as US, EU, and Canada, law requires refrigerant recovery. This option is assumed to be practiced at 80% in the baseline in developed countries, and 30% in developing countries (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	1-3	$26.19	$3.40	$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-eq.}}$
1: CEC (2005)

Industry Acceptance Level: Widely practiced in developed countries. Although this option is widely accepted in developed countries, the penetration remains low in many developing countries, due to a lack of available capital infrastructure as well as a lack of legislation design. Therefore, further growth is especially expected in developing countries (IEA, 2003).

Limitations: Reduction efficiency is uncertain because it may vary depending on technician technique and equipment type (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Household Refrigeration

Technology: Use of hydrocarbons (C.1.1.1.2)

Description of the Technology:
Hydrocarbons have the same good thermal properties as HFCs and therefore, can replace HFC refrigerant in new manufactured household refrigerators and freezers (IEA, 2003; USEPA, 2001). Currently used refrigerants include HC-600a, HC-290, and HC-1270 (USEPA, 2006b). HC-600a system, the growing hydrocarbon refrigerant, has about 40% smaller charge size of a typical household refrigeration unit (USEPA, 2006b).

Effectiveness: Good

Implementability: The conversion of hydrocarbon in hermetic systems has been proved to be easy; in large part, it can be converted at the manufacturing site. In Europe, hydrocarbon is rapidly becoming popular for new household refrigeration (IEA, 2003).

Reliability: Although there have been some cases reported of fire during the manufacture processes in some countries, there is no health risk for a domestic size refrigeration system (IEA, 2003).

Maturity: Hydrocarbon refrigerant, especially isobutene (HC-600a) is continuing to grow in European market share, and also gaining market share in Japan (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Use of hydrocarbons[1]	15	-	100	2-7	$38.49	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}eq.}$
1: IEA (2003)

Industry Acceptance Level: It has been used in large part of Europe; however, it has not occurred in North America yet, because of its perceived risks and low acceptance of HC as a refrigerant. To date, 120 million HC refrigerators have been estimated to be manufactured, and sold in Germany, Spain, Sweden, England, France, Turkey, Argentina, Australia, Brazil, China, Cuba, India, Indonesia, and Japan (IEA, 2003).

Limitations: This flammable alternative cause safety concern and therefore requires redesigns in the manufacturing process that would increase costs. It also requires additional engineering and testing, development of standards and service procedures, and training of technicians before commercialization (USEPA, 2006b).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Residential Air-conditioners and Heat Pumps

Technology: Refrigerant recovery/recycling (C.1.1.2.1)

Description of the Technology:
Practicing refrigerant recovery for reuse or destruction can significantly reduce HFC emissions. Recovery options apply a refrigerant recovery device that transfers refrigerant into a storage container prior to servicing or disposing equipment. After the recovery process, the refrigerant contained in the storage container either is recharged back into the source equipment, cleaned through the use of recycling devices, purified for resale at a reclamation facilities, or disposed safely in an environmentally-safe manner (IEA, 2003; USEPA, 2001).

Effectiveness: It can reduce emissions by 95% (USEPA 2006b; CEC, 2005).

Implementability: Technically applicable in all regions

Reliability: No risk and uncertainty associated with this option is recognized (IEA, 2003).

Maturity: This option is assumed to be practiced at 80% in the baseline in developed countries, and 30% in developing countries (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	-	10	95	10	\$26.19	\$3.40	\$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005)

Industry Acceptance Level: Although this option is widely accepted in developed countries, the penetration remains low in many developing countries, due to a lack of available capital infrastructure as well as a lack of legislation design. Therefore, further growth is especially expected in developing countries (IEA, 2003).

Limitations: Reduction efficiency is uncertain because it may vary depending on technician technique and equipment type (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Residential Air-conditioners and Heat Pumps

Technology: Leak repair (C.1.1.2.2)

Description of the Technology:
There are many types of repairs applicable to reduce leaks in residential air-conditioning, but the major repairs include installment of new purge systems, replacement or removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Technically applicable to all regions

Reliability: Good

Maturity: Law in many developed countries already regulates maximum allowable leak rates, but further leak reduction improvements, such as upgrades or replacement, are still possible (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	5	90	0.2-0.5	\$27.55	\$0.00	\$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Major modifications to large air-conditioning systems are well adopted and have widely penetrated in developed countries (USEPA, 2001).

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Motor Vehicle Air Conditioners

Technology: Refrigerant recovery/recycling (C.1.1.3.1)

Description of the Technology:
Practicing refrigerant recovery for reuse or destruction can significantly reduce HFCs emissions. Recovery options apply a refrigerant recovery device that transfers refrigerant into a storage container prior to servicing or disposing equipment. After the recovery process, the refrigerant contained in the storage container either is recharged back into the source equipment, cleaned through the use of recycling devices, purified for resale at a reclamation facilities, or disposed safely in an environmentally-safe manner (IEA, 2003; USEPA, 2001).

These practices are already in baseline in many refrigeration systems because of the cost efficiency yielded by the reuse and re-sold processes; however, small equipments such as motor vehicle air conditioning systems (MVACs) has less recoverable charges, thus being less cost effective. Yet, refrigerant recovery/recycling is believed to be the most common option to reduce HFC emissions from MVAC systems (IEA, 2003). Moreover, these technological options are being evaluated by the industry and new information is continuously being developed (CEC, 2005)

Effectiveness: It can reduce total emissions by 95% (USEPA, 2001).

Implementability: Technically applicable in all regions

Reliability: No risk and uncertainty associated with this option is recognized (IEA, 2003).

Maturity: Refrigerant recovery equipment is widely available and used extensively in developed countries. In some countries such as US, EU, and Canada, refrigerant recovery is required by law (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	10	$26.19	$3.40	$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & IEA (2003)

Industry Acceptance Level: This option is widely accepted in developed countries (IEA, 2003).

Limitations: Reduction efficiency is uncertain because it may vary depending on technician technique and equipment type (IEA, 2003).

Sources of Information:

1. Baker, J.A. (1998) "Mobile Air Conditioning and Global Warming". *Proc. Phoenix Alternate Refrigerant Forum 1998,* Suntest Engineering, Scottsdale, AZ.

2. California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.
3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. Fisher, S.K.; Tomlinson, J.J.; Hughes, P.J. (1994) “Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-kind and Next Generation CFC and HCFC Alternatives”, prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
7. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
8. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
9. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
10. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
12. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
15. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
16. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.
17. Wertenbach, J.; Maue, J.; Volz, W. (1996) “CO_2 Refrigeration System in Automobile Air Conditioning”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Motor Vehicle Air Conditioners

Technology: Improved HFC-134a systems (C.1.1.3.2)

Description of the Technology:
This technology improves the construction and dimensions of the flexible hose, connection of the system components, and compressor shaft seals. It is estimated that this reduced leakage accounts for 15g refrigerant emission reduction per year (CARB, 2004). By adopting this option, it is also assumed that MVAC fuel efficiency would improve by 25-30% (CEC, 2005). In addition, indirect emissions can be reduced by improving system efficiency; through the use of oil separators and externally controlled swash-plate compressors (USEPA, 2006b).

Effectiveness: Good

Implementability: Research ongoing

Reliability: Improved HFC-134a systems are expected to become commercially available sooner than other alternatives such as HFC-152a or CO_2.

Maturity: Improved HFC-134a systems are estimated to be available in 2009 or in the near term (CEC, 2005). It is assumed to achieve the greatest market penetration in North America, where industry is not readily moving away from HFC-134a use. Countries with environmental initiatives such as Europe, Australia, and Japan are expected to switch to other options including CO_2 or HFC-152a beyond 2010 (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Improved HFC-134a systems[1]	-	1	18	15	$404.80	$0.00	$168.30

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005)

Industry Acceptance Level: Research ongoing

Limitations: Technology has not been fully developed yet.

Sources of Information:

1. Baker, J.A. (1998) "Mobile Air Conditioning and Global Warming". *Proc. Phoenix Alternate Refrigerant Forum 1998,* Suntest Engineering, Scottsdale, AZ.
2. California Air Resources Board (2004) "Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles", California Air Resources Board, August 6, 2004.

3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. Fisher, S.K.; Tomlinson, J.J.; Hughes, P.J. (1994) “Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-kind and Next Generation CFC and HCFC Alternatives”, prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
7. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
8. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
9. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
10. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
12. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
15. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
16. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.
17. Wertenbach, J.; Maue, J.; Volz, W. (1996) “CO_2 Refrigeration System in Automobile Air Conditioning”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Motor Vehicle Air Conditioners

Technology: HFC-152a systems (C.1.1.3.3)

Description of the Technology:
HFC-152a has considerably lower GWP and therefore, is in use as a drop-in replacement for HFC-134a. This option can be used in both direct expansion and secondary loop MVAC systems (USEPA, 2006b). HFC-152a is also available for use in a “low-leak” system, which is expected to further reduce the emission. This option is expected to be in use beginning in 2012 (CEC, 2005).

Effectiveness: It can reduce total emissions by 89% as a result of its lower GWP (CEC, 2005).

Implementability: HFC-152a direct expansion systems in MVACs would not require any significant changes when being shifted from HFC-134a systems except for the safety enforcement such as refrigerant detector systems (USEPA, 2006b).

Reliability: Good

Maturity: The technology is still in the development phase (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:
This abatement option is estimated to have a capital cost of approximately $25/car; there is no available cost related data for the low-leak system (CARB, 2004). It has the lowest capital cost than any other MVAC options (USEPA, 2006b).

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
HFC-152a systems[1]	-	0	89	15	$192.33	$0.00	$54.15

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005)

Industry Acceptance Level: HFC-152a will have a wide market share in Europe, Australia, and Japan; however, these countries might be shifting to CO_2 systems once it become commercially available. On the other hand, it will gain more and more share in North America, once it become available, because it is easy to shift from HFC-134a (USEPA, 2006b).

Limitations: Although the flammability of HFC-152a is less than hydrocarbons, safety systems would still be necessary; personnel training would also be needed (USEPA, 2006b).

Sources of Information:

1. Baker, J.A. (1998) “Mobile Air Conditioning and Global Warming”. *Proc. Phoenix Alternate Refrigerant Forum 1998,* Suntest Engineering, Scottsdale, AZ.
2. California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.

3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. Fisher, S.K.; Tomlinson, J.J.; Hughes, P.J. (1994) “Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-kind and Next Generation CFC and HCFC Alternatives”, prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
7. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
8. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
9. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
10. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
12. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
15. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
16. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.
17. Wertenbach, J.; Maue, J.; Volz, W. (1996) “CO_2 Refrigeration System in Automobile Air Conditioning”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Motor Vehicle Air Conditioners

Technology: Use of CO_2 (C.1.1.3.4)

Description of the Technology:
Use of CO_2 as the refrigerant in motor vehicle air conditioners (MVAC) is a significant technical option with high emission reduction potentiality. This technology uses a transcritical vapor cycle which differs from conventional MVAC systems, hence requiring innovative design and engineering; the study on such new systems are ongoing by many vehicle manufacturers in cooperation with system suppliers (USEPA, 2006b; IEA, 2003). The system is believed to have comparable energy efficiency to HFC-134a systems, and moreover, it has the lowest GWP among any candidate refrigerants (IEA, 2003). Major development is needed for system components to accommodate the extremely high CO_2 pressure level. However, studies have also been carried out to develop a "low-pressure" CO_2 hybrid system (IEA, 2003). These technological options are being evaluated by the industry and new information is continuously being developed (CEC, 2005).

Effectiveness: Since it has a GWP of 1, it can potentially reduce total emissions by 100%.

Implementability: Potentially applicable to all regions

Reliability: Further development on safety systems may be required to detect and vent accidentally released CO_2 in order to ensure the passengers safety (IEA, 2003).

Maturity: Further development in performance and safety is needed before the CO_2 system is commercialized and replaces HFC-134a. It is assumed that the first systems will be commercialized within 4 - 7 years (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Use of CO_2[1]	12	0	100	15	$611.97	$0.00	$86.03

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & IEA (2003)

Industry Acceptance Level: Future market penetration will vary based on user acceptance, and it is possible that some regions may not adopt this technology depending on perceived risks of CO_2 systems. Due to the high capital costs, it will not be able to be adopted in developing countries until later years (USEPA, 2006b).

Limitations: There are still many limitations for this technology due to the technical immaturity (IEA, 2003; USEPA, 2001).

Sources of Information:

1. Baker, J.A. (1998) "Mobile Air Conditioning and Global Warming". *Proc. Phoenix Alternate Refrigerant Forum 1998,* Suntest Engineering, Scottsdale, AZ.

2. California Air Resources Board (2004) “Staff report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Emissions from Motor Vehicles”, California Air Resources Board, August 6, 2004.
3. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
4. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
5. Fisher, S.K.; Tomlinson, J.J.; Hughes, P.J. (1994) “Automobile Air Conditioning: Energy and Global Warming Impacts of Not-in-kind and Next Generation CFC and HCFC Alternatives”, prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
7. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
8. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
9. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
10. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
11. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
12. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
15. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
16. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.
17. Wertenbach, J.; Maue, J.; Volz, W. (1996) “CO_2 Refrigeration System in Automobile Air Conditioning”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Chillers

Technology: Options for emission reduction including leak repair (C.1.1.4)

Description of the Technology:
There are many types of repairs applicable to reduce leaks in chillers, the major repairs include installment of new purge systems, replacement/removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Good

Reliability: This is a primary option for emission reduction.

Maturity: Law in many developed countries already regulates maximum allowable leak rates, but further leak reduction improvements, such as upgrades or replacement, are still possible (USEPA, 2006b).

Environmental Benefits: High GWP-gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	5	90	0-4	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Good

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Retail Food Refrigeration

Technology: Leak repair (C.1.1.5.1)

Description of the Technology:
There are many types of repairs applicable to reduce leaks in retail food refrigeration, the major repairs include installment of new purge systems, replacement or removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Leak repair options range from simple repairs to major system upgrades (USEPA, 2006b).

Reliability: This is a primary option for emission reduction.

Maturity: Law in many developed countries already regulates maximum allowable leak rates, but further leak reduction improvements, such as upgrades or replacement, are still possible (USEPA, 2006b).

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	10	90	3-14	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Major modifications to large refrigeration systems are well adopted and have widely penetrated in developed countries (USEPA, 2001).

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) "The State of the Art of Hydrocarbon Technology in Household Refrigeration", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) "Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) "A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies". Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) "Report of the Refrigeration, Air Conditioning and Heat Pumps", Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) "Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants" in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) "Low-charge Refrigeration for Supermarkets", IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Retail Food Refrigeration

Technology: Alternative systems (C.1.1.5.2)

Description of the Technology:
Alternative systems use CO_2, ammonia, hydrocarbons or a combination of these as refrigerants in place of HFC refrigerants for retail food applications. These systems are comparatively new but have high energy-efficiency potential. Although studies are underway, experts believe that the systems can be further improved, for both low and medium temperature refrigeration, by adapting better system designs (IEA, 2003).

Effectiveness: Good

Implementability: Good

Reliability: Early stage of development. Safety concerns associated with this option remain.

Maturity: Many new technologies designed to use these alternative refrigerants are currently at the stage of experimental tests and design improvements (IEA, 2003). Some CO_2 systems are commercialized and in use in Denmark (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Alternative systems[1]	15	-	100	6-27	$188.10	-$1.41	$2.76

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003)

Industry Acceptance Level: A growing number of applications are adopting such alternative systems in many countries, especially in Europe. In Denmark, CO_2 systems are in use for retail food applications with built-in alarms to ensure the safety (IEA, 2003).

Limitations: There are many uncertainties remain due to the immaturity of these alternatives such as: safety, cost of designing, total cost performance, purchasing equipment, potential loss of operational efficiency and indirect emission impacts, refrigerant containment, long-term reliability, and compressor performance (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Retail Food Refrigeration

Technology: Ammonia secondary loop systems (C.1.1.5.3)

Description of the Technology:
Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling, hence reduce emissions of HFCs. Secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases. Thus, it operates at reduced charges and allows less leak rates (US Climate Change, 2005; USEPA, 2001). Ammonia is a toxic substance but can replace HFCs in these systems, because the system design does not let this substance contact customers. The system has great benefits in that it requires less maintenance, has more efficient defrost, and longer shelf life than direct expansion, the conventional systems (IEA, 2003; USEPA, 2001)

Effectiveness: Good

Implementability: Ammonia is a toxic substance that the use in a confined space is a major concern; however, due to its chemical characteristics, the leaks are easily detectable with application of safety equipments. Besides, since it is lighter than air, it is easy to disperse in the event of release (IEA 2003; USEPA 2006b).

Reliability: To ensure its safety, current systems contain regulatory systems to control pressures. Also, emergency diffusion systems and a series of safety relief valves are installed (IEA, 2003).

Maturity: Widely adopted and growing in Europe**.**

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Ammonia secondary loop systems[1]	20	10	100	6-27	$115.98	$12.89	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: These systems have been in use for decades in Europe; however, it is heavily regulated in North America (IEA, 2003; ACHR News, 2000).

Limitations: The toxicity and flammability would require major design modifications for the majority of traditional HFC systems (USEPA, 2006b). A revision of codes may be necessary in US to allow the expanded use of ammonia in new equipment types (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Retail Food Refrigeration

Technology: HFC secondary loop systems (C.1.1.5.4)

Description of the Technology:
Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling, hence reduce emissions of HFCs. Secondary loop systems segregate refrigerant-containing equipment to a separate and centralized location, and use a benign fluid to transfer heat from the food display cases. Thus, by centralizing refrigerants to one or a few locations, the technology allows systems to have lower leak rates and operate at reduced charges (IEA, 2003; USEPA, 2006b). It also allows economical installation of leak-detection equipment to alert system operators when HFC refrigerant emissions occur (US Climate Change, 2005).

The system has great benefits in that it requires less maintenance, has more efficient defrost, and longer shelf life than direct expansion, the conventional systems (IEA, 2003; USEPA, 2001).

Effectiveness: Good

Implementability: Applicable to all regions; easy to operate and maintain (IEA, 2003)

Reliability: Good

Maturity: The U.S./Australia Climate Action Partnership is currently exploring the possibility of building and monitoring a typical and secondary-loop store to verify its potential benefits (US Climate Change, 2005).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
HFC secondary loop systems[1]	20	10-20	100	6-27	$30.93	$12.89	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Not well adopted in the US. Supermarkets are unwilling to install new technologies until the benefits are proven. However, its potential market penetration is high, for this technical option can be introduced to newly constructed stores and/or retrofitted stores (US Climate Change, 2005; USEPA, 2001).

Limitations: The system is especially effective for low-temperature (e.g., frozen foods) systems; however, the number of these systems is limited.

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Retail Food Refrigeration

Technology: Replacing direct expansion systems with distributed systems (C.1.1.5.5)

Description of the Technology:
Distributed refrigeration features multiple smaller refrigeration units located closer to the food display cases, eliminating the need for excessive refrigerant piping throughout the store to reach a mechanical room sited away from the food, thereby, reducing leaks of HFCs. It also reduces the refrigerant charge and minimizes the need for a dedicated mechanical room containing multiple compressor racks (IEA, 2003). These systems are more advantageous compared to the conventional direct expansion systems in energy efficiency and thus, long-term cost performance (IEA, 2003).

Effectiveness: Good

Implementability: These systems have been proved to be relatively easy to operate and maintain.

Reliability: These technologies have minimal risks and uncertainties.

Maturity: Widely available and in actual use

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replacing direct expansion systems with distributed systems[1]	20	10-20	100	6-27	$82.15	-$6.84	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Commonly accepted in retail food refrigeration

Limitations: Because the systems place refrigerant charge throughout the building, the potential risk of accidental refrigerant release is large; the use of flammable or highly toxic refrigerants is not feasible (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

4. Kruse, H. (1996) "The State of the Art of Hydrocarbon Technology in Household Refrigeration", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) "Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) "A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies". Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) "Report of the Refrigeration, Air Conditioning and Heat Pumps", Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) "Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants" in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) "Low-charge Refrigeration for Supermarkets", IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Cold Storage Warehouse

Technology: Leak repair (C.1.1.6.1)

Description of the Technology:
Leak repair can especially reduce HFC emissions in a large system like cold storage. There are many types of repairs applicable to reduce leaks in cold storage, but the major repairs include installment of new purge systems, replacement or removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Leak repair options range from simple repairs to major system upgrades (USEPA, 2006b).

Reliability: This is a primary option for emission reduction.

Maturity: Well developed and regulated

Environmental Benefits: High GWP-gas emission reduction

Cost Effectiveness: Major equipment upgrades are expensive

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	10	90	6-15	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Major modifications to large refrigeration systems are well adopted and have widely penetrated in developed countries (USEPA, 2001).

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Cold Storage Warehouse

Technology: Alternative systems (C.1.1.6.2)

Description of the Technology:
Alternative systems use CO_2, ammonia, hydrocarbons or a combination of these as refrigerants in place of HFC refrigerants for cold storage applications. These systems are comparatively new but have high energy-efficiency potential. Although studies are underway, experts believe that the systems can be further improved, for both low and medium temperature refrigeration, by adapting better system designs (IEA, 2003).

Effectiveness: Good

Implementability: Potentially applicable to all regions

Reliability: Early stage of development; safety concerns associated with this option remain.

Maturity: Many new technologies designed to use these alternative refrigerants are currently at the stage of experimental tests and design improvements (IEA, 2003). Some CO_2 systems are commercialized and in use (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Alternative systems[1]	15	-	100	11-31	$188.10	-$1.41	$2.76

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003)

Industry Acceptance Level: A growing number of applications are adopting such alternative systems in many countries especially in Europe.

Limitations: There are many uncertainties remain due to the immaturity of these alternatives such as: safety, cost of designing, total cost performance, purchasing equipment, potential loss of operational efficiency and indirect emission impacts, refrigerant containment, long-term reliability, and compressor performance (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Cold Storage Warehouse

Technology: Ammonia secondary loop systems (C.1.1.6.3)

Description of the Technology:
Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling, hence reduce emissions of HFCs. Secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases. Thus, it operates at reduced charges and allows less leak rates (US Climate Change, 2005; USEPA, 2001). Ammonia is a toxic substance but can replace HFCs in these systems, because the system design does not let this substance contact customers.

The system has great benefits in that it requires less maintenance, has more efficient defrost, and longer shelf life than direct expansion, the conventional systems (IEA, 2003; USEPA, 2001)

Effectiveness: Good

Implementability: Ammonia is a toxic substance that the use in a confined space is a major concern; however, due to its chemical characteristics, the leaks are easily detectable with application of safety equipments. Besides, since it is lighter than air, it is easy to disperse in the event of release (IEA 2003; USEPA 2006b).

Reliability: To ensure its safety, current systems contain regulatory systems to control pressures. Also, emergency diffusion systems and a series of safety relief valves are installed (IEA, 2003).

Maturity: Widely adopted and growing in some regions (Europe)

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Ammonia secondary loop systems[1]	20	10	100	11-31	$115.98	$12.89	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: These systems have been in use for decades in Europe, however, it is heavily regulated in North American region (IEA, 2003; ACHR News, 2000).

Limitations: The toxicity and flammability would require major design modifications for the majority of traditional HFC systems (USEPA, 2006b). A revision of codes is necessary in US to allow the expanded use of ammonia in new equipment types (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Cold Storage Warehouse

Technology: HFC secondary loop systems (C.1.1.6.4)

Description of the Technology:
Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling, hence reduce emissions of HFCs. Secondary loop systems segregate refrigerant-containing equipment to a separate and centralized location, and use a benign fluid to transfer heat from the food display cases. Thus, by centralizing refrigerants to one or a few locations, the technology allows systems to have lower leak rates and operate at reduced charges (IEA, 2003; USEPA, 2006b). It also allows economical installation of leak-detection equipment to alert system operators when HFC refrigerant emissions occur (US Climate Change, 2005).

The system has great benefits in that it requires less maintenance, has more efficient defrost, and longer shelf life than direct expansion, the conventional systems (IEA, 2003; USEPA, 2001).

Effectiveness: Good

Implementability: Applicable to all regions; easy to operate and maintain (IEA, 2003)

Reliability: Good

Maturity: Well developed technologically

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
HFC secondary loop systems[1]	20	10-20	100	11-31	\$30.93	\$12.89	\$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: EPA has carried out a test for this system; various manufacturers are also conducting their own proprietary research. Its potential market penetration is high, for this technical option can be introduced to newly constructed storages and/or retrofitted storages (US Climate Change, 2005; USEPA, 2001).

Limitations: The system is especially effective for low-temperature (e.g., frozen foods) systems; however, the number of these systems is very limited.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Cold Storage Warehouse

Technology: Replacing direct expansion systems with distributed systems (C.1.1.6.5)

Description of the Technology:
Distributed Refrigeration features multiple smaller refrigeration units located closer to the refrigerated display cases, eliminating the need for excessive refrigerant piping throughout the store to reach a mechanical room sited away from the food, thereby, reducing leaks of HFCs. It also reduces the refrigerant charge and minimizes the need for a dedicated mechanical room containing multiple compressor racks (IEA, 2003). These systems are more advantageous compared to the conventional direct expansion systems in energy efficiency and thus, long-term cost performance (IEA, 2003).

Effectiveness: Good

Implementability: These systems have been proved to be relatively easy to operate and maintain.

Reliability: These technologies have minimal risks and uncertainties.

Maturity: Widely available and in actual use.

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replacing direct expansion systems with distributed systems[1]	20	10-20	100	11-31	$82.15	-$6.84	$1.58

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Commonly accepted in retail food refrigeration

Limitations: Because the systems place refrigerant charge throughout the building, the potential risk of accidental refrigerant release is large; the use of flammable or highly toxic refrigerants is not feasible. In some cases, safety codes will not permit the use of such flammable refrigerants, and thus store operators will not apply these systems (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Refrigerated Transport

Technology: Refrigerant recovery/recycling (C.1.1.7)

Description of the Technology:
Practicing refrigerant recovery for reuse or destruction can significantly reduce HFCs emissions. Recovery options apply a refrigerant recovery device that transfers refrigerant into a storage container prior to servicing or disposing equipment. After the recovery process, the refrigerant contained in the storage container either is recharged back into the source equipment, cleaned through the use of recycling devices, purified for resale at a reclamation facilities, or disposed safely in an environmentally-safe manner (IEA, 2003, USEPA, 2001).

These practices are already in baseline in many refrigeration systems because of the cost efficiency yielded by the reuse and re-sold processes; however, small equipments such as refrigerated transport has less recoverable charges, thus being less cost effective. Yet, refrigerant recovery/recycling is believed to be the most feasible option to reduce HFC emissions from refrigerated transport systems (IEA, 2003).

Effectiveness: It can reduce total emissions by 95% (USEPA, 2001).

Implementability: Technically applicable in all regions

Reliability: No risk and uncertainty associated with this option is recognized (IEA, 2003).

Maturity: Well developed

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	10	10	95	10	$26.19	$3.40	$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Widely practiced in developed countries.

Limitations: Proper equipment instructions must be implemented to minimize the refrigerant release into the atmosphere as well as safety risk for technicians. Similarly, reduction efficiency is uncertain because it may vary depending on technician technique and equipment type (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Industrial Process Refrigeration

Technology: Leak repair (C.1.1.8.1)

Description of the Technology:
There are many types of repairs applicable to reduce leaks in industrial process refrigeration, the major repairs include installment of new purge systems, replacement or removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Leak repair options range from simple repairs to major system upgrades (USEPA, 2006b).

Reliability: This is a primary option for emission reduction.

Maturity: Law in many developed countries already regulates maximum allowable leak rates, but further leak reduction improvements, such as upgrades or replacement, are still possible (USEPA, 2006b).

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	10	90	1-5	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{CO2\text{-}eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Major modifications to large refrigeration systems are well adopted and have widely penetrated in developed countries (USEPA, 2001).

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) "The State of the Art of Hydrocarbon Technology in Household Refrigeration", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) "Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) "A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies". Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) "Report of the Refrigeration, Air Conditioning and Heat Pumps", Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) "Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants" in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) "Low-charge Refrigeration for Supermarkets", IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Industrial Process Refrigeration

Technology: Alternative systems (C.1.1.8.2)

Description of the Technology:
Alternative systems use CO_2, ammonia, hydrocarbons or a combination of these as refrigerants in place of HFC refrigerants for industrial process refrigeration applications. These systems are comparatively new but have high energy-efficiency potential. Although studies are underway, experts believe that the systems can be further improved, for both low and medium temperature refrigeration, by adapting better system designs (IEA, 2003).

Effectiveness: Good

Implementability: Potentially applicable to all regions

Reliability: Early stage of development; safety concerns associated with this option remain.

Maturity: Many new technologies designed to use these alternative refrigerants are currently at the stage of experimental tests and design improvements (IEA, 2003). Some CO_2 systems are commercialized and in use (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Alternative systems[1]	15	-	100	2-9	$188.10	-$1.41	$2.76

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-eq.}}$
1: IEA (2001) & IEA (2003)

Industry Acceptance Level: A growing number of applications are adopting such alternative systems in many countries, especially in Europe.

Limitations: There are many uncertainties remain due to the immaturity of these alternatives such as: safety, cost of designing, total cost performance, purchasing equipment, potential loss of operational efficiency and indirect emission impacts, refrigerant containment, long-term reliability, and compressor performance (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Industrial Process Refrigeration

Technology: Ammonia secondary loop systems (C.1.1.8.3)

Description of the Technology:
Better equipment design and store layout can lead to a reduction in the amount of refrigerant needed for a given amount of product cooling, hence reduce emissions of HFCs. Secondary loop systems circulate a secondary coolant or brine from the central refrigeration system to the display cases. Thus, it operates at reduced charges and allows less leak rates (US Climate Change, 2005; USEPA, 2001). Ammonia is a toxic substance but can replace HFCs in these systems, because the system design does not let this substance contact customers.

The system has great benefits in that it requires less maintenance, has more efficient defrost, and longer shelf life than direct expansion, the conventional systems (IEA, 2003; USEPA, 2001)

Effectiveness: Good

Implementability: Ammonia is a toxic substance that the use in a confined space is a major concern; however, due to its chemical characteristics, the leaks are easily detectable with application of safety equipments. Besides, since it is lighter than air, it is easy to disperse in the event of release (IEA 2003; USEPA 2006b).

Reliability: To ensure its safety, current systems contain regulatory systems to control pressures. Also, emergency diffusion systems and a series of safety relief valves are installed (IEA, 2003).

Maturity: The actual market penetration depends on the potential risks of these technologies, because it affects the acceptance degree from manufacturers, end users, regulators, and insurance companies (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Ammonia secondary loop systems[1]	20	10	100	2-9	$116	$12.89	$2.76

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-eq.}}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: These systems have been in use for decades in Europe; however, it is heavily regulated in North America (IEA, 2003; ACHR News, 2000).

Limitations:
The toxicity and flammability would require major design modifications for the majority of traditional HFC systems (USEPA, 2006b). A revision of codes is necessary in US to allow the expanded use of ammonia in new equipment types (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
3. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) "The State of the Art of Hydrocarbon Technology in Household Refrigeration", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) "Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) "A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook", *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) "Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies". Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) "Report of the Refrigeration, Air Conditioning and Heat Pumps", Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) "Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants" in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) "Low-charge Refrigeration for Supermarkets", IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Commercial Unitary Air-conditioning

Technology: Refrigerant recovery/recycling (C.1.1.9.1)

Description of the Technology:
Practicing refrigerant recovery for reuse or destruction can significantly reduce HFCs emissions. Recovery options apply a refrigerant recovery device that transfers refrigerant into a storage container prior to servicing or disposing equipment. After the recovery process, the refrigerant contained in the storage container either is recharged back into the source equipment, cleaned through the use of recycling devices, purified for resale at a reclamation facilities, or disposed safely in an environmentally-safe manner (IEA, 2003, USEPA, 2001). Refrigerant recovery/recycling are considered as viable technological options to reduce HFC emissions (IEA, 2003).

Effectiveness: It can reduce total emissions by 95% (USEPA, 2001).

Implementability: Technically applicable in all regions

Reliability: No risk and uncertainty associated with this option is recognized (IEA, 2003).

Maturity: Refrigerant recovery equipment is widely available and used extensively in developed countries. In some countries such as US, EU, and Canada, law requires refrigerant recovery. This option is assumed to be practiced at 80% in the baseline in developed countries, and 30% in developing countries (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Refrigerant recovery/recycling[1]	-	10	95	10	$26.19	$3.40	$1.69

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005)

Industry Acceptance Level: Widely practiced in developed countries (IEA, 2003).

Limitations: Proper equipment instructions must be implemented to minimize the refrigerant release into the atmosphere as well as safety risk for technicians. Similarly, reduction efficiency is uncertain because it may vary depending on technician technique and equipment type (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Commercial Unitary Air-conditioning

Technology: Leak repair (C.1.1.9.2)

Description of the Technology:
There are many types of repairs applicable to reduce leaks in commercial unitary air-conditioning, the major repairs include installment of new purge systems, replacement or removal of the motor, installment of new refrigerant metering, and replacement of flare joints, gaskets, or seals (USEPA, 2001). Usually, those options are very expensive, so they are often feasible only for large equipments. In addition, new and advanced leak reduction technologies are emerging and expected to lower the costs over time (IEA, 2003). Technologies such as early warning signals are in the final stage of development (USEPA, 2006b).

Effectiveness: Good

Implementability: Leak repair options range from simple repairs to major system upgrades (USEPA, 2006b).

Reliability: This is a primary option for emission reduction.

Maturity: Law in many developed countries already regulates maximum allowable leak rates, but further leak reduction improvements, such as upgrades or replacement, are still possible (USEPA, 2006b).

Environmental Benefits: High-GWP gases emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leak repair[1]	5	5	90	0-4	$27.55	$0.00	$3.05

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: Major modifications to large air-conditioning systems are well adopted and have widely penetrated in developed countries (USEPA, 2001).

Limitations: The reduction efficiency of this option varies on a case-by-case basis since it depends on the age of equipment and quality of repair. Similarly, the total percent of abatement that is achievable through this option is uncertain (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

3. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
4. Kruse, H. (1996) “The State of the Art of Hydrocarbon Technology in Household Refrigeration”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
5. Mathur, G.D. (1996) “Performance of Vapor Compression Refrigeration System with Hydrocarbons: Propane, Isobutane, and 50/50 Mixture of Propane/isobutane”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
6. Paul, J. (1996) “A Fresh Look at Hydrocarbon Refrigeration: Experience and Outlook”, *Proc. International Conference on Ozone Protection Technologies*, October 21-23, Washington, D.C.
7. Sand, J.R.; Fischer, S.K.; Baxter, V.D. (1997) “Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies”. Prepared by Oak Ridge National Laboratory for Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, Oak Ridge, TN.
8. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
9. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
10. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
11. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
12. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
13. UNEP - United Nations Environment Programme (1998) “Report of the Refrigeration, Air Conditioning and Heat Pumps”, Technical Options Committee; Nairobi, December 1998.
14. van Gerwen, R.; Vervoerd, M. (2000) “Emission reduction of non-CO_2 Greenhouse Gases Used as Refrigerants” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
15. Walker, D. (2000) “Low-charge Refrigeration for Supermarkets”, IEA Heat Pump Center Newsletter, vol. 18, no. 1, p. 13-16.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/End-uses of MDIs

Technology: Dry powder inhalers (C.1.2.1)

Description of the Technology:
Dry Powder Inhaler (DPIs) consists of micro dry powders that can replace metered dose inhalers (MDIs) to treat asthma and chronic obstructive pulmonary disease (USEPA, 2001). There are also newly developed medications that would be swallowed, rather than inhaled, which may be introduced over the next 10 to 20 years (USEPA, 2006b).

Effectiveness: It has proven to be very successful where it is applicable (USEPA, 2001).

Implementability: Due to stringent performance and toxicology specifications, the applicability of this alternative is limited to patients who are able to inhale robustly enough to transport the powder to the lungs (USEPA, 2001).

Reliability: Successful but limited usage

Maturity: It has been successfully used with most anti-asthma drugs; it account for 85% of inhaled medication. These options are especially wide-adopted in Europe (USEPA 2001). For example, it accounts for more than 65% of inhaled medication in Holland (UNEP, 2002).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Dry powder inhalers[1]	15	5	100	50	$294.21	$0.00	0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: In the US, DPIs usage is on the rise in the United States; it made up 14% of the total US market share as of mid-2002 (UNEP, 2002). In Europe, it is widely adopted. The use of DPIs is estimated to expand more in the future (IEA, 2003).

Limitations: They may not be applicable to all patients or all drugs; they are not suitable for young children, the elderly, and persons with severe asthma (IEA, 2003; USEPA, 2001). Another concern is that the powder may aggregate under hot and humid climates (USEPA, 2006b).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/End-uses of Consumer Products and Specialty Products

Technology: Substitution with lower GWP HFCs (C.1.2.2.1)

Description of the Technology:
HFC-152a possesses a lower flammability risks than hydrocarbons and dimethyl ether as well as low GWP of 120. Therefore, it is expected to be a good replacement for HFC-134a (USEPA, 2001).

Effectiveness: Good

Implementability: Good

Reliability: This option is very effective for the emission reductions from the aerosol sectors (USEPA 2004).

Maturity: HFC-152a has been in market for products such as electronic equipment dusters, boat and safety “air” horns, and tire inflators (IEA, 2003; USEPA, 2001). It is also used as a propellant for laboratory and experimental uses (IEA, 2003; IEA GHG, 2001). The incremental maximum market penetration of this option is assumed to be 50% in 2020 (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Substitution with lower GWP HFCs[1]	10	25	91	48	\$0.75	-\$2.52	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: Good

Limitations: HFC-152a possesses moderate flammability risks that might not be viable in some applications; it is assumed that this technical option potentially abates 60% of HFC-134a emissions, which accounts for 80% of total non-MDI aerosol emissions (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/End-uses of Consumer Products and Specialty Products

Technology: VOC propellants (C.1.2.2.2)

Description of the Technology:
VOC propellants that can be used in consumer products are usually mixtures of propane, butane, and isobutene. Dimethyl ether is another alternative (IEA, 2003; USEPA, 2001). The most attractive point of this option is its affordability; the disadvantages are the flammability and VOC emission (USEPA, 2006b).

Effectiveness: Good

Implementability: Good

Reliability: Good option for some sectors.

Maturity: Currently, it is the primary propellant in the non-MDI aerosol market (USEPA, 2001). Due to flammability and VOC concerns, further market penetration is very limited; it is assumed to share the market by only 10% (USEPA, 2006b).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
VOC propellants[1]	10	10	100	40	$0.44	-$5.60	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: Since the CFCs were banned in the US, many consumer products manufacturers including spray deodorants and hair sprays markets have adopted either hydrocarbon propellants or NIK substitutes (IEA, 2003).

Limitations: Flammability and VOC emissions are of major risks. Thus, the feasibility of this option may be limited; it is assumed to abate only half of HFC-134a emissions (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO$_2$ Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/End-uses of Consumer Products and Specialty Products

Technology: Not-in-kind (NIK) products (C.1.2.2.3)

Description of the Technology:
The successful Not-in-Kind (NIK) substitutes include solid applicators, finger-trigger pumps, powder formulations, sticks, rollers, brushes, nebulizers, and bag-in-can/piston-can systems. These options are often better and more cost-effective than HFC-propelled aerosols. It has replaced HFCs especially in areas where HFC property is not specifically needed for a certain end-use (USEPA, 2006b).

Effectiveness: Good

Implementability: Good

Reliability: No safety/health risks recognized (IEA, 2003).

Maturity: It has already applied to most products that could switch to NIK, therefore further market penetration might not be expected (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness: Very cost effective

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Not-in-kind (NIK) products[1]	10	10	100	100	$0.34	-$5.26	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/MT$_{\text{CO2-Eq.}}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: The technology has already well-adopted in the aerosol market, ever since the CFCs were banned (USEPA, 2001).

Limitations: Since it has already been used in most of the available market, no further market penetration is expected.

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO$_2$ Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Solvent Uses

Technology: Improved equipment and cleaning processes (C.1.3.1)

Description of the Technology:
Attempts to reduce emissions and save costs have led to significant improvements in the existing technology (USEPA, 2006b). Improved containment such as better solvent bath enclosure and better vapor condensing systems can reduce emissions of HFCs and PFCs used in solvent cleaning. Similarly, better engineering controls such as increasing freeboard height, installing freeboard chillers, less drag-out losses, and using automatic hoists will minimize emissions and losses of existing solvents (USEPA, 2006b; March Consulting Group, 1999). Such practices, combined with proper operation and maintenance, can reduce emissions from solvent process by as much as 46 to 70% (USEPA, 2006b).

Effectiveness: Varies

Implementability: Good

Reliability: Good

Maturity: Since this option has already practiced in many countries including the United States, it is not expected to further expand; by 2010 and beyond, the solvent equipment in use will either already have been retrofitted or replaced by new equipment. Therefore, the market penetration is assumed to drop down from 5% to 0% by 2020 (USEPA, 2006b).

Environmental Benefits: High-GWP gases emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Improved equipment and cleaning processes[1]	10	0	46 - 90	90 - 100	\$370.37	\$0.00	\$27.84

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: Retrofitting equipment is being adopted on newer vapor degreasers (IEA, 2003).

Limitations: This option is not viable for older equipment that should rather be replaced (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.

3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.
4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Solvent Uses

Technology: Aqueous cleaning (C.1.3.2)

Description of the Technology:
Aqueous cleaning processes use water and detergents as a solvent. A hydrocarbon solvent combines with a surfactant to remove contaminants. The process consists of four stages: washing, rinsing, drying, and wastewater disposal (IEA, 2003).

Effectiveness: This technology can successfully displace HFCs and PFCs usage in some solvent applications.

Implementability: Good

Reliability: Some technical limitations, such as substrate corrosion, inadequate performance for applications with complex parts, still remain (USEPA, 2006b).

Maturity: Aqueous cleaning technologies have been used for over 25 years in developed countries (UNEP, 1999). Further market penetration is not expected in the United States, where the market prefers fluorinated solvents such as HFCs and HFEs (USEPA, 2006b).

Environmental Benefits: High-GWP gases emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Aqueous cleaning[1]	10	5	100	90 - 100	$40.00	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: Many electronics and metal cleaning sectors worldwide have already adopted this technology (IEA, 2003).

Limitations: There is an uncertainty in cost performance for the wastewater treatment processes as well as energy consumption (USEPA, 2001).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Solvent Uses

Technology: Semi-aqueous cleaning (C.1.3.3)

Description of the Technology:
The semi-aqueous cleaning process uses a solution consisting of hydrocarbon and surfactant to remove contaminants. An example of a solvent/surfactant blend is a terpene/water combination blended with glycol ethers (UNEP, 1999). The products are then rinsed with water.

Effectiveness: This technology can successfully displace HFCs and PFCs usage in some solvent applications.

Implementability: Good

Reliability: They have good cleaning ability, suppressed vapor pressure, and reduced evaporative loss. Some technical limitations, such as substrate corrosion, inadequate performance for applications with complex parts, still remain (USEPA, 2006b).

Maturity: Semi-aqueous cleaning technologies have been available for years (UNEP, 1999). Further market penetration is not expected in the United States, where the market prefers fluorinated solvents such as HFCs and HFEs (USEPA, 2006b).

Environmental Benefits: High-GWP gases emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Semi-aqueous cleaning[1]	10	3	100	90 - 100	$22.22	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: Many electronics and metal cleaning sectors worldwide have already adopted this technology (IEA, 2003).

Limitations: Flammability and VOC emissions are of concerns but can be solved by improving the equipment design (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Solvent Uses

Technology: Alternative solvents (C.1.3.4)

Description of the Technology:
In electronics, metal, and some precision cleaning end uses, alternative organic solvents with lower GWPs are being introduced and integrated into the industry. These solvents including HFCs, HFEs, hydrocarbons, alcohols, volatile methyl siloxanes, brominated solvents, and non-ODS chlorinated solvents, can replace PFC/PFPEs, CFCs, and HCFCs. Since there is only a little use of HFC, PFC/PFPE, and HCFC in the metal and electronic cleaning end uses, these alternative solvents are primarily used for precision cleaning and carrier fluid applications instead of CFC-113 and methyl chloroform.

Recently, HFE solvents are especially being accepted as an effective alternative in solvent cleaning because of its low toxicity, non-flammability, zero ozone depleting potential, and low GWPs. It successfully replaced PFCs, HFCs, CFC-113, 1,1,1-trichloroethane, and HCFCs in precision cleaning (IEA, 2003).

Effectiveness: Good

Implementability: Variable; HFEs have a limited feasibility for HFC 4310mee solvents (IEA, 2003).

Reliability: HFEs are a viable alternative where the applicability is feasible (IEA, 2003).

Maturity: HFEs and the various azeotropic formulations based on HFEs are already in wide use in many developed countries.

Environmental Benefits: High-GWP gases emission reduction

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Alternative solvents[1]	10	30	85	5 - 100	\$0.00	\$1.29	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), & USEPA (2004)

Industry Acceptance Level: HFE solvents are gaining acceptance in the US industry due to their availability, safety, and effectiveness (USEPA, 2004). This option is estimated to grow its market penetration in the United States to 60% by 2020. This means all PFC solvent emissions and more than half of the HFC solvent emissions (USEPA, 2006b).

Limitations: Technical applicability limitation exists in some industries, which use specific azeotropes or HFCs blends to replace with HFEs. There is no explicit study data for PFCs emissions from solvent sectors, hence, lack of information on HFE applicability to PFC (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.
4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Foam Sector

Technology: Replace HFC-134a in appliance with hydrocarbons (C.1.4.1)

Description of the Technology:
HCs have lower GWPs compared to HFCs as well as more cost effective, thus making this option viable. HCs include propane, butane, isobutene, n-pentane, isopentane, cyclopentane, and isomers of hexane (IEA, 2003).

Effectiveness: The energy efficiency is lower when foams are blown with HCs than HCFC (approximately 85% of HCFC performance), but can be improved technologically.

Implementability: Some safety uncertainties associated with HCs flammability, performance, and environmental impacts remained. Fire risks can be lowered by employing a large amount of flame-retardants and/or a higher quality fire-retardant (IEA, 2003).

Reliability: Good

Maturity: Good

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Replace HFC-134a in appliance with hydrocarbons[1]	25	25	100	0-2	$105.79	-$3.19	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: It is especially accepted in Europe. However, the penetration is low in the spray foam industry due to the uncertain safety risks (UNEP, 2002).

Limitations: Flammability, performance, and contribution to the ground level ozone and smog are the major concerns of option. HCs require tight safety precautions in manufacturing, storage, handling, transport, and customer use, thus, factory upgrades and sufficient employee training are needed (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Foam Sector

Technology: Replace HFC-245fa in appliance with hydrocarbons (C.1.4.2)

Description of the Technology:
HCs have lower GWPs compared to HFCs as well as more cost effective, thus making this option viable. HCs include propane, butane, isobutene, n-pentane, isopentane, cyclopentane, and isomers of hexane (IEA, 2003).

Effectiveness: The energy efficiency is lower when foams are blown with HCs than HCFC (approximately 85% of HCFC performance), but can be improved technologically.

Implementability: Some safety uncertainties associated with HCs flammability, performance, and environmental impacts remained. Fire risks can be lowered by employing a large amount of flame-retardants and/or a higher quality fire-retardant (IEA, 2003).

Reliability: Good

Maturity: Good

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace HFC-245fa in appliance with hydrocarbons[1]	25	15	100	0-10	$144.40	$32.35	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: It is especially accepted in Europe. However, the penetration is low in the spray foam industry due to the uncertain safety risks (UNEP, 2002).

Limitations: Flammability, performance, and contribution to the ground level ozone and smog are the major concerns of option. HCs require tight safety precautions in manufacturing, storage, handling, transport, and customer use, thus, factory upgrades and sufficient employee training are needed (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO$_2$ Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Foam Sector

Technology: Replace HFC-245fa in sprays with hydrocarbons (C.1.4.3)

Description of the Technology:
HCs have lower GWPs compared to HFCs as well as more cost effective, thus making this option viable. HCs include propane, butane, isobutene, n-pentane, isopentane, cyclopentane, and isomers of hexane (IEA, 2003).

Effectiveness: The energy efficiency is lower when foams are blown with HCs than HCFC (approximately 85% of HCFC performance), but can be improved technologically.

Implementability: Some safety uncertainties associated with HCs flammability, performance, and environmental impacts remained. Fire risks can be lowered by employing a large amount of flame-retardants and/or a higher quality fire-retardant (IEA, 2003).

Reliability: Good

Maturity: Good

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace HFC-245fa in sprays with hydrocarbons[1]	25	10	100	0-26	$7.81	-$3.82	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/MT$_{\text{CO2-Eq.}}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: It is especially accepted in Europe. However, the penetration is low in the spray foam industry due to the uncertain safety risks (UNEP, 2002).

Limitations: Flammability, performance, and contribution to the ground level ozone and smog are the major concerns of option. HCs require tight safety precautions in manufacturing, storage, handling, transport, and customer use, thus, factory upgrades and sufficient employee training are needed (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO$_2$ Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Foam Sector

Technology: Replace HFC-245fa in sprays with water-blown CO_2 (C.1.4.4)

Description of the Technology:
In this technology, water and polymeric isocyanate react to generate CO_2 blowing agent *in situ* that is then used in foam blowing (IEA, 2003; UNEP, 1998). During manufacture, no ODS or high GWP gases are emitted; there are limited health and safety risks during processing (USEPA, 2006b).

Effectiveness: Fair

Implementability: Fair

Reliability: Foams produced using the CO_2/water blowing agents have performance limitations in thickness, conductivity, dimensional stability, and density, when compared to HCFC- and HFC-blown foams (UNEP, 2002; IEA, 2003).

Maturity: Research ongoing; research is needed in order to further develop and improve the technology.

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace HFC-245fa in sprays with water-blown CO_2[1]	25	5	100	0-26	\$2.23	\$23.97	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: CO_2/water blown foam applications are widely used in Europe (IEA, 2003).

Limitations: The final products of the CO_2 blowing agent are poor in water proofing quality. This can be improved by increasing the amount of polymeric isocyanurate, which is not suitable for many existing equipments (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Foam Sector

Technology: Replace HFC-134a/152a in extruded polystyrene with water-blown CO_2 (C.1.4.5)

Description of the Technology:
In this technology, water and polymeric isocyanate react to generate CO_2 blowing agent *in situ* that is then used in foam blowing (IEA, 2003; UNEP, 1998). During manufacture, no ODS or high GWP gases are emitted; there are limited health and safety risks during processing (USEPA, 2006b). The foams manufactured with this option is assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam (USEPA, 2006b).

Effectiveness: Fair

Implementability: Fair

Reliability: Foams produced using the CO_2/water blowing agents have performance limitations in thickness, conductivity, dimensional stability, and density, when compared to HCFC- and HFC-blown foams (UNEP, 2002; IEA, 2003).

Maturity: Research ongoing; research is needed in order to further develop and improve the technology.

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Replace HFC-134a or 152a in extruded polystyrene with water-blown CO_2[1]	25	0	100	37-100	$8.89	-$0.14	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: CO_2/water blown foam applications are widely used in Europe (IEA, 2003).

Limitations: The final products of the CO_2 blowing agent are poor in water proofing quality. This can be improved by increasing the amount of polymeric isocyanurate, which is not suitable for many existing equipments (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.

3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.
4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Fire-Fighting Sector

Technology: Water mist systems (C.1.5.1)

Description of the Technology:
Water mist system is different from the traditional water-spray systems or conventional sprinklers in that it uses special nozzles that designed to produce very tiny droplets under low, medium, or high pressure; consequently, it reduces significant amount of water required to extinguish fires (IEA, 2003; UNEP, 2001).

Effectiveness: Good

Implementability: Theoretically, water mist system can be used in all Class B (fuel) hazards, under an appropriate temperature condition (USEPA, 2001) and are currently in use for storage and machinery spaces, shipboard accommodation, combustion turbine enclosures, light and ordinary hazard sprinkler applications, and flammable and combustible liquid machinery (UNEP, 2001).

Reliability: Several technical hurdles are to be solved so that this technological option can attain a wide market penetration.

Maturity: The technology is commercially available but still under research in order to extend its applicability to a wider degree (IEA, 2003).

Environmental Benefits: HFCs emission reduction

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
Water mist systems[1]	10	50	100	1-4	-$35.71	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: Because of the high potentiality, this option is expected to develop further; researchers have been positive about overcoming the technological challenges.

Limitations: Thus far, technical applicability is limited to fire extinguishing applications that already have good fire test protocols based on empirically tested system performance (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection

Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Fire-Fighting Sector

Technology: Inert gas systems (C.1.5.2)

Description of the Technology:
Inert gas systems use argon, nitrogen carbon dioxide, or a blend of these gases to extinguish fires (UNEP, 2001).

Effectiveness: Good

Implementability: Inert gas systems can be applied for the standard HFC systems in Class A (ordinary combustible) total flooding applications. This includes electronics as well as telecommunications applications (IEA, 2003)

Reliability: For most Class A fire hazards, it provides an equivalent level of both fire protection and life safety/health protection (USEPA, 2006b).

Maturity: Commercially available; however, several risks may prevent the option from widely use and therefore, further research are needed (IEA, 2003).

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Inert gas systems[1]	10	20	100	15-76	$98.57	$3.57	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001), IEA (2003), USEPA (2004), & UNEP (2002)

Industry Acceptance Level: The inert gas systems are assumed to increase over time, as old systems are replaced to new systems (IEA, 2003).

Limitations: This system may not be applicable for situations that fire expansion is rapid, because of its slow discharge time (4 to 6 times slower than standard HFC systems); the additional space and weight necessary for the installation of the system may not be suitable for many systems which infrastructure are already fixed (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
3. D. Little (1999) “Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications”, by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.

4. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) “UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report”, Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
8. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) “Analysis of Cost to Abate Ozone-depleting Substitute Emissions”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) “The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol”, HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) “Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment”, Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) “Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment”, Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Substitution of ODS/Sterilization

Technology: Options for reducing high-GWP emission from sterilization (C.1.6)

Description of the Technology:
Sterilization is used to control microorganisms and pathogens during the growing, collecting, storing and distribution of various foods including grains, vegetable, and fruits. Many low temperature sterilization techniques utilize an ethylene oxide/CFC mixture. Currently the USEPA Vintaging Model assumes that this sector has not transitioned to any HFC or PFC uses as an ODS substitute (Godwin *et al.*, 2003). No technological options for reducing HFCs or PFCs from this sector were found from the literature search.

Effectiveness: Not applicable

Implementability: Not applicable

Reliability: Not applicable

Maturity: Not applicable

Cost Effectiveness: Not applicable

Industry Acceptance Level: Not applicable

Limitations: Not applicable

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. D. Little (1999) "Global Comparative Analysis of HFC and Alternative Technologies for Refrigeration, Air Conditioning, Foam, Solvent, Aerosol Propellant and Fire Protection Applications", by J. Dieckmann and H. Magid, A.D. Little, Cambridge, reference number 49468, United Kingdom, August 1999.
4. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
5. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
6. March Consulting Group (1999) "UK Emissions of HFCs, PFCs, and SF_6 and Potential Emission Reduction Options: Final Report", Commissioned by the Department of the Environment, Transport and the Regions, United Kingdom, January 1999.
7. U.S. Climate Change Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

8. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
9. U.S. Environmental Protection Agency (2004) "Analysis of Cost to Abate Ozone-depleting Substitute Emissions", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 430-R-04-006, June 2004.
10. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
11. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
12. UNEP - United Nations Environment Programme (1999a) "The Implications to the Montreal Protocol of the Inclusion of HFCs, and PFCs in the Kyoto Protocol", HFC and PFC Task Force of the Technology and Economic Assessment Panel, New York, October 1999.
13. UNEP - United Nations Environment Programme (1999b) "Report of the Solvents, Coatings, and Adhesive Technical Options Committee (STOC): 1998 Assessment", Ozone Secretariat, April 1999.
14. UNEP - United Nations Environment Programme (2002) "Report of the Aerosols, Sterilants, Miscellaneous Uses and Carbon Tetrachloride: 2002 Assessment", Technical Options Committee, United Nations Environment Programme.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Electric Power Transmission and Distribution Systems

Technology: Leakage reduction and recovery (C.2.1)

Description of the Technology:
Leaks from the equipment and venting of the gas during equipment servicing and disposal of equipment are the main sources of emissions. Normal procedures require taking units out of service to search for SF_6 leaks.

A laser leak detection system is capable of finding leaks accurately without any modifications or physical connections to circuit breakers. The advantages over traditional leak detection procedures are the ability to perform leak detection without having to take equipment out of service and the dramatic reduction in time necessary to detect a leak (USEPA, 2001).

Effectiveness: This is one of the most effective options to reduce emissions from this sector.

Implementability: Technically available to all manufactures of gas insulated electrical equipment (IEA, 2003)

Reliability: This is a basic and promising option to effectively abate SF_6 emissions from electric power systems because of its availability, cost performance, and implementability (CEC, 2005; IEA, 2003).

Maturity: Well developed technologically and widely practiced (CEC, 2005)

Environmental Benefits: High-GWP gas emission reduction. If thoroughly implemented in the United States, leak detection and repair could reduce SF_6 emissions from this sector by about 20% (USEPA, 2004).

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Leakage reduction and recovery[1]	10	100	100	100	$10.96	$1.81	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: USEPA (2001) & CEC (2005); 2: IEA (2003)

Industry Acceptance Level: Many U.S. utilities already implement cost-effective leak detection and repair. The GasVue laser camera, a laser leak detection system developed with the support of the Electric Power Research Institute (EPRI) by Laser Imaging Systems of Punta Gorda, Florida, has been successfully used at a wide range of utilities in the United States and abroad (Moore, 1999).

Limitations: SF_6-containing equipment leakage varies on the type of equipment: old/new, size of operational voltage, manufacturer, weather, etc. Therefore, the applicability may be limited on the region or country of use (IEA, 2003).

Sources of Information:

1. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

2. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.

3. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.

4. Environment Canada (1998) “Powering GHG Reductions through Technology Advancement”, Clean Technology Advancement Division, Environment Canada.

5. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

7. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.

8. McCracken, G.A.; Christiansen, R.; Turpin, M. (2000) “The Environmental Benefits of Remanufacturing: Beyond SF_6 Emission Reduction”, *Proc. International Conference on* SF_6 *and the Environment: Emission Reduction Strategies*, November 1-3, San Diego, CA.

9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.

10. McRae, T. (2000) “GasVue and the Magnesium Industry: Advanced SF_6 Leak Detection”, *Proc. International Conference on* SF_6 *and the Environment: Emission Reduction Strategies*, November 1-3, San Diego, CA.

11. Moore, T. (1999) “Seeing SF_6 in a New Light”, *EPRI Journal*, Summer 1999, Palo Alto, CA.

12. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.

13. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

14. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.

15. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006

16. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Electric Power Transmission and Distribution Systems

Technology: Improved SF_6 Recovery for switch gear manufacture (C.2.2)

Description of the Technology:
SF_6 is an expensive gas which is characterized by high degree of stability. Therefore, it is convenient to recover the gas and reuse, adopting the same procedures as in the manufacturing phases. Recycling equipment such as recycling gas cart systems allows SF_6 gas to be captured; it provides a method to remove gas from the electrical equipment, and filter it for reuse (IEA, 2003).

Effectiveness: One of the most promising options

Implementability: Technically available to all manufactures of gas insulated electrical equipment (IEA, 2003)

Reliability: Good

Maturity: Well developed and widely in use

Environmental Benefits: High-GWP gas emission reduction. It is estimated that SF_6 recycling can eliminate at least 10% of total SF_6 emissions from U.S. electric power systems (USEPA, 2001).

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Improved SF_6 recovery for electric gas insulated switch gear manufacture[1]	15	-	100	30-60	$1.84	$0.01 – 0.6	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003)

Industry Acceptance Level: Widely in use at all regions (IEA, 2003)

Limitations: It is estimated that SF_6 emissions during manufacturing and testing of gas-insulated equipment are 30-50% of total equipment charge size (IEA, 2001)

Sources of Information:

1. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
2. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.
3. Ecofys (1999) "Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union", Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.

4. Environment Canada (1998) “Powering GHG Reductions through Technology Advancement”, Clean Technology Advancement Division, Environment Canada.
5. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
6. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
7. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
8. McCracken, G.A.; Christiansen, R.; Turpin, M. (2000) “The Environmental Benefits of Remanufacturing: Beyond SF_6 Emission Reduction”, *Proc. International Conference on* SF_6 *and the Environment: Emission Reduction Strategies*, November 1-3, San Diego, CA.
9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
10. Moore, T. (1999) “Seeing SF_6 in a New Light”, *EPRI Journal*, Summer 1999, Palo Alto, CA.
11. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
12. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
14. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
15. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.
16. Coordinating Committee for the Associations of Manufacturers of Industrial Electrical Switchgear and Control-gear in the European Union (2002), "Environment Sustainability Approach Capiel HV Part D Switchgear and SF_6 Gas", CAPIEL HV-ESDD1-R1-1.02, www.capiel-electric.com/publicats, January, 2002.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: CVD cleaning emission reduction/NF_3 remote clean (C.3.1)

Description of the Technology:
The Novellus's *In-situ* NF_3 Clean Technology system introduces NF_3 directly into the CVD process chamber where the gas is dissociated in plasma. NF_3 possesses a high GWP very close to that of C_2F_6, however, the chemical's overall high efficiency leads to the reduction of gas emissions and thus, less climate impact as compared to C_2F_6 (US Climate Change, 2005).

The NF_3 Remote Clean™ Technology developed by Applied Materials uses an upstream (remote) device to dissociate NF_3 using argon gas at a 99% efficiency rate. In addition, chamber cleaning times are 30 to 50% faster than baseline C_2F_6 clean times. The system converts the source gas to active N and F atoms in the plasma, upstream of the process chamber. These electrically neutral atoms can selectively remove material in the chamber. The remote cleaning technology differs from *in situ* technology in that the NF_3 dissociates into plasma before entering the chamber rather than being dissociated inside the chamber. The byproducts of Remote Clean™ include HF, F_2, and other gases, of which all but F_2 are removed by facility acid scrubber systems (US Climate Change, 2005).

Effectiveness: Good

Implementability: All fabrication facilities

Reliability: Good

Maturity: Good.

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
CVD cleaning emission reduction – NF_3 remote clean[1]	5	90	90	60	$90.76	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$

1: CEC (2005) & USEPA (2001)

Industry Acceptance Level: NF_3 use is rapidly gaining market share in the semiconductor industry for CVD chamber cleaning because of its high process efficiency.

Limitations: This option is only applicable to control emissions from chamber cleaning processes; it accounts for approximately 70% of total fabrication emissions (IEA, 2003).

Sources of Information:

1. Applied Materials (1999) "Catalytic Abatement of PFC Emissions", *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
4. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.
5. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
6. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
7. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
8. International SEMATECH (1999) “Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocarbons (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber” Presented at: A Partnership for PFC Emissions Reductions, Semicon Southwest 99, Austin, Texas, October 1999.
9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
10. Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
11. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
12. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
14. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
15. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: CVD cleaning emission reduction/C_3F_8 replacement (C.3.2)

Description of the Technology:
C_3F_8 is a potential drop-in replacement for C_2F_6 in some chemical vapor deposition clean and etch processes; its high utilization during etch may offset its high GWP (IEA, 2003; USEPA, 2001).

Although PFCs are not completely eliminated in these cases, overall emissions and potential impacts may be lower than in a scenario without the substitution. Therefore, replacing high GWP gases with environmentally benign substitutes for chemical vapor deposition clean and dielectric etch processes are the preferred option (USEPA, 2001).

Effectiveness: Good

Implementability: All fabrication facilities

Reliability: Although this option does not achieve the same emission reduction that NF_3 achieves, it is considerably feasible in cost performance. Thus, its excellent process performance as well as cost savings makes this alternative option attractive (US Climate Change, 2005; USEPA, 2001).

Maturity: Well developed

Environmental Benefits: Use of C_3F_8 will reduce high GWP emissions by 85% relative to the standard C_2F_6 process (USEPA, 2001).

Cost Effectiveness:

Technology	**Lifetime (yrs)**	**MP (%)**	**RE (%)**	**TA (%)**	**Capital cost**	**Annual cost**	**Benefits**
CVD cleaning emission reduction – C_3F_8 replacement[1]	5	-	100	70-90	$0.00	$0.00	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: IEA (2003) & USEPA (2001)

Industry Acceptance Level: C_3F_8 is reported in commercial applications at fabricating facilities owned by AMD, Motorola, and Texas Instruments (US Climate Change, 2005).

Limitations: This option is only applicable to control emissions from chamber cleaning processes; it accounts for approximately 70% of total fabrication emissions (IEA, 2003; USEPA, 2001).

Sources of Information:

1. Applied Materials (1999) “Catalytic Abatement of PFC Emissions”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

3. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
4. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.
5. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
6. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
7. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
8. International SEMATECH (1999) “Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocarbons (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber” Presented at: A Partnership for PFC Emissions Reductions, Semicon Southwest 99, Austin, Texas, October 1999.
9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
10. Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
11. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
12. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
14. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
15. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: Point-of-use plasma abatement (C.3.3)

Description of the Technology:
Plasma abatement technologies rely on the basic idea that larger exhaust molecules are broken into fragments in the plasma and then recombine in new ways, in the presence of other fragments, to form a new set of exhaust gases that may then be removed by existing waste-treatment systems. Thus, the high GWP gases react with fragments of the additive gas (H_2, O_2, H_2O, or CH_4) in the plasma and form low molecular weight by-products with little or no GWP. Wet scrubbers can then remove these product molecules (US Climate Change, 2005). The small plasma source are located in the foreline of an etch tool or in the gas line between the process tool and the main pump, and before the dry pump nitrogen purge such that it can access the undiluted exhaust stream (IEA, 2003).

The two widely used technologies are: the Litmas “Blue” and “Red”, and AMAT’s Pegasys™ POU unit. Litmas’s “Blue” uses an inductively coupled radio frequency plasma source to transform high-GWP exhaust gases from etchers, and the “Red” which transforms the exhausts from plasma-enhanced chemical vapor deposition chambers using microwaves. AMAT’s Pegasys™ POU unit integrates cold-plasma abatement technology with popular etchers, which makes the abatement unit transparent to process engineers (US Climate Change, 2005).

Effectiveness: Litmas reported emission reductions from 97% to 99% for its “Blue” POU device; AMAT’s capacity coupled device (Pegasys II™) claims typically more than 95% reduction in emissions (IEA, 2003).

Implementability: It can be applied to the entire etch processes without ant interference to the process. It also requires very little floor space to install (US Climate Change, 2005).

Reliability: This option has been demonstrated to attain the reduction efficiency of more than 97% when water vapor is used as an additive gas (USEPA, 2001).

Maturity: Well developed and commercialized.

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Point-of-use plasma abatement[1]	5	55	97	10	\$50.81	\$1.45	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & USEPA (2001)

Industry Acceptance Level: Currently, plasma abatement is believed to be the most popular option in the industry. It accounts for 55% of the total emission reduction in the etching sector, being the largest reduction option (US Climate Change, 2005).

Limitations: This option can be applied only for etch processes, which account for approximately 30% of fabrication emissions.

Sources of Information:

1. Applied Materials (1999) “Catalytic Abatement of PFC Emissions”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
4. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.
5. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
6. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
7. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
8. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
9. Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
10. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
11. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
12. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
13. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
14. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: Thermal destruction or processing units (C.3.4)

Description of the Technology:
Thermal destruction technology can be applied to reduce PFCs emissions from both the CVD chamber cleaning and etching processes. It is installed downstream of the process tool so that it does not affect the manufacturing process and performances.

High GWP emissions are oxidized in a natural gas-fired burner before the combustion products are removed by the on-site waste treatment systems. Burner system requires pretreatment of inlet streams to reduce the loads of unused deposition/etchant gases and particles that can block the system. Hydrofluoric acid formed in thermal destruction systems may be removed via POU scrubbers to prevent exceeding scrubber design limits (US Climate Change, 2005; USEPA, 2001).

Effectiveness: Good

Implementability: The Edwards TPU 4214 (oxidation with advanced burner technology) is applicable for all high GWP emissions and achieves more than 99% destruction efficiency.

Reliability: Several PFC thermal destruction systems can effectively abate some PFCs, but only a few have been proven to abate all PFCs at greater than 90% destruction efficiency.

Maturity: Several PFC thermal destruction systems are commercially available, but the Edwards TPU 4214 is the only thermal-destruction device in commercial use and represents a favored POU solution for chemical vapor deposition cleaning processes (US Climate Change, 2005).

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Thermal destruction or processing units[1]	5	20	90	40	$93.39	$8.98	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & USEPA (2001)

Industry Acceptance Level: This option is technologically matured and well adopted, despite of other preferable abatement options such as process improvements.

Limitations: The thermal destruction system requires a combustion fuel and use significant amounts of cooling water that creates an additional waste stream. In addition, it produces NOx emissions, which are regulated air pollutants. (Applied Materials, 1999).

Sources of Information:

1. Applied Materials (1999) “Catalytic Abatement of PFC Emissions”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
4. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.
5. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
6. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
7. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
8. International SEMATECH (1999) “Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocarbons (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber” Presented at: A Partnership for PFC Emissions Reductions, Semicon Southwest 99, Austin, Texas, October 1999.
9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
10. Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
11. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
12. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
14. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
15. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: Catalytic decomposition system (C.3.5)

Description of the Technology:
Catalytic destruction systems are similar to thermal destruction units in that the system is installed in the process after the turbo pump that dilutes the exhaust stream prior to feeding it through the scrubber and emitting the scrubbed gases into the atmosphere. There is no back-flow into the etching tool itself, which could adversely affect the performance of the etching tool. Therefore, it minimizes potential adverse impacts on manufacturing processes (USEPA, 2001; IEA, 2003).

High GWP emissions are oxidized in an electrically heated catalyst before the combustion products are removed by the on-site waste treatment systems, and because of this catalytic process, it operates at lower temperatures.

Effectiveness: Good

Implementability: The Hitachi system is applicable to CF_4, C_2F_6, C_4F_8, and SF_6.

Reliability: The reduction efficiency of this technological option is more than 99% for CF_4, C_2F_6, C_4F_8, and SF_6 (US Climate Change, 2005).

Maturity: Catalytic Decomposition System (Hitachi) is commercialized and widely being adopted (IEA, 2003).

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
Catalytic decomposition system[1]	5	20	98	40	\$67.35	\$5.32	\$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US\$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & USEPA (2001)

Industry Acceptance Level: It has adopted by fabrications worldwide (IEA, 2003).

Limitations: Catalytic systems require pretreatment of inlet streams to reduce the loads of unused deposition/etchant gases and particles that can block burners or clog catalysts. The design must reflect a minimum concentration and flow of PFC within the exhaust stream; therefore, off-the-shelf systems can be applied only for facilities with certain stream or process specifications (USEPA, 2001). Etch and chamber specific reductions can only reduce emissions from their respective percentage of the total emissions.

Sources of Information:

1. Applied Materials (1999) “Catalytic Abatement of PFC Emissions”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

2. California Energy Commission (2005) “Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California”, a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.
3. California Energy Commission (2006) “Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004”, final staff report, December 22, 2006.
4. Ecofys (1999) “Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union”, Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.
5. Intergovernmental Panel on Climate Change - IPCC (2001) “Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change”, The Third Assessment Report - Working Group I, January 2001.
6. International Energy Agency (2001) “Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals”, Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.
7. International Energy Agency (2003) “Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases”, Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.
8. International SEMATECH (1999) “Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocarbons (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber” Presented at: A Partnership for PFC Emissions Reductions, Semicon Southwest 99, Austin, Texas, October 1999.
9. McFarland, M.; van Gerwen, R. (2000) “Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios” in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.
10. Motorola (1999) “Long-term Evaluation of Litmus “Blue” Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement”, *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.
11. Öko-Recherche (1999) “Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany”, A study commissioned by the German Environmental Protection Agency, Germany, October 1999.
12. U.S. Climate Technology Program (2005) “Technology Options for the Near and Long Term”, U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2001) “U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities”, Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.
14. U.S. Environmental Protection Agency (2006a) “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004” Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006
15. U.S. Environmental Protection Agency (2006b) “Global Mitigation of Non-CO_2 Greenhouse Gases”, Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

Non-CO_2 Greenhouse Gases: High-GWP Gases

Source/Sectors: Semiconductor Sector

Technology: PFC recapture/recovery (C.3.6)

Description of the Technology:
PFC recapture/recovery is a feasible option for treating the waste streams of entire fabrications. This technology separates un-reacted and/or process-generated PFCs from other gases using a membrane for further processing; the reprocessed PFCs are either reused or concentrated for subsequent off-site disposal (IEA, 2003; USEPA, 2001). Currently available capture systems are guaranteed to remove 90 % of emissions; in general, removal efficiency of C_2F_6, CF_4, SF_6, and C_3F_8 is higher (more than 90%), and CHF_3 and NF_3 removal efficiencies is lower (50 - 60%). In addition to membrane separation, Praxair/Ecosys cryogenic capture system and, MEGASORB and BOC pressure swing absorption systems are reported as new recapture technologies; these systems have shown low capture efficiencies so far. DuPont is investigating a technological option for the disposition of C_2F_6-containing mixture; the research is ongoing for the repurification and the off-site destruction of C_2F_6 (US Climate Change, 2005; USEPA, 2001). One example of process optimization is to use end-point detectors and/or process parameter variation to determine the optimal fluorocarbon utilization to reduce excess emissions.

Effectiveness: Good

Implementability: The technology can be applied to both sources of emissions: the etching and the CVD chamber cleaning processes.

Reliability: Good

Maturity: The technologies including Praxair/Ecosys and Edwards cryogenic capture systems have already commercialized, but have not been widely adopted worldwide; there are no published reports of commercial uses for the MEGASORB and BOC system (US Climate Change, 2005).

Environmental Benefits: High-GWP gas emission reduction

Cost Effectiveness:

Technology	Lifetime (yrs)	MP (%)	RE (%)	TA (%)	Capital cost	Annual cost	Benefits
PFC recapture/recovery[1]	5	8	90	100	$40.52	$13.20	$0.00

Note: MP: market penetration; RE: reduction efficiency; TA: technical applicability; costs are in year 2000 US$/$MT_{CO2\text{-}Eq.}$
1: CEC (2005) & USEPA (2001)

Industry Acceptance Level: This technology is currently low in demand because NF_3 cleaning systems do not leave sufficient PFCs in the stream to make gas recovery economically viable.

Limitations: All options require considerable pretreatment to remove undesirable substances such as corrosives particles and moisture from the exhaust gas stream.

Sources of Information:

1. Applied Materials (1999) "Catalytic Abatement of PFC Emissions", *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

2. California Energy Commission (2005) "Emission Reduction Opportunities for Non-CO_2 Greenhouse Gases in California", a report prepared by ICF Consulting for California Energy Commissions, CEC-500-2005-121, July 2005.

3. California Energy Commission (2006) "Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004", final staff report, December 22, 2006.

4. Ecofys (1999) "Reduction of the Emissions of HFCs, PFCs and SF_6 in the European Union", Commissioned by DG XI of the European Commission, authored by H. Heijnes, M. van Brummelen, and K. Blok, April 1999.

5. Intergovernmental Panel on Climate Change - IPCC (2001) "Summary for Policy Makers: A Report of Working Group I of the Intergovernmental Panel on Climate Change", The Third Assessment Report - Working Group I, January 2001.

6. International Energy Agency (2001) "Abatement of Emissions of Other Greenhouse Gases - Engineered Chemicals", Report Number PH3/35, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, February 2001.

7. International Energy Agency (2003) "Building the Cost Curves for the Industrial Sources of Non-CO_2 Greenhouse Gases", Report Number PH4/25, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom, October 2003.

8. International SEMATECH (1999) "Motorola Evaluation of the Applied Science and Technology, Inc. (ASTex) ASTRON Technology for perfluorocarbons (PFC) Emissions Reductions on the Applied Materials DxL Chemical Vapor Deposition (CVD) Chamber" Presented at: A Partnership for PFC Emissions Reductions, Semicon Southwest 99, Austin, Texas, October 1999.

9. McFarland, M.; van Gerwen, R. (2000) "Fluorine Compounds: Emissions Inventories, Options for Control and Their Implementation and Resulting Scenarios" in Non-CO_2 Greenhouse Gases: Scientific Understanding, Control and Implementation (edited by J. Van Ham *et al.*), Kluwer Academic Publishers, London.

10. Motorola (1999) "Long-term Evaluation of Litmus "Blue" Inductively-Coupled Plasma Device for Point-of-Use PFC and HFC Abatement", *Proc. Semicon Southwest 99 – A Partnership for PFC Emission Reduction*, October 18, Austin, Texas.

11. Öko-Recherche (1999) "Emissions and Reduction Potentials of Hydrofluorocarbons, Perfluorocarbons and Sulphur Hexafluoride in Germany", A study commissioned by the German Environmental Protection Agency, Germany, October 1999.

12. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.

13. U.S. Environmental Protection Agency (2001) "U.S. High GWP Gas Emissions 1990 – 2010: Inventories, Projections, and Opportunities", Office of Air and Radiation, U.S. Environmental Protection Agency, EPA 000-F-97-000, June 2001.

14. U.S. Environmental Protection Agency (2006a) "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 to 2004" Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-002, June 2006

15. U.S. Environmental Protection Agency (2006b) "Global Mitigation of Non-CO_2 Greenhouse Gases", Office of Atmospheric Programs, United States Environmental Protection Agency, EPA-430-R-06-005, June 2006.

APPENDIX D

Technological Options for Emission Reduction of Black Carbon

1. - Mobile Sources
2. - Stationary Sources

Non-CO_2 Greenhouse Gases: Black Carbon

Source/Sectors: Mobile Sources

Technology: Options to reduce black carbon emission from mobile sources (D.1)

Description of the Technology:
Mobile sources, especially those associate with diesel, are responsible for most of the BC emissions, most technological options for BC emission reduction found from the literature search are for diesel vehicles and engines. Basically, BC is removed in the process that is mainly aimed for removal of particulate matter. Specific technological options to reduce BC emissions from mobile sources include:

- Diesel particle filters (DPFs) – DPFs remove PM from the diesel exhaust through physical filtration. DPFs must be supplemented with means of self-cleaning (regeneration) to remove the collected carbon and organic particles. This is done by adding heat to the exhaust, raising temperature high enough to oxidize carbon to gaseous carbon dioxide. Nonetheless, all DPFs still require periodic maintenance to clean-out ash that accumulates from the non-organic carbon components of the engine oil (Clean Air Task Force, 2005).
- Catalyst-based DPFs – The added catalyst effectively lowers the temperature required for regeneration of the filters. The catalyst can be poisoned by sulfur; therefore, this type of DPFs can only be used with diesel fuel of low sulfur content (Clean Air Task Force, 2005).
- Diesel oxidation catalysts (DOCs) – DOCs use the same type of catalyst material as that in the catalyst-based DPFs, but applied to a flow-through monolith, without the physical filter (Clean Air Task Force, 2005; Lyons, 2003). This is mainly for reduction of OC-based particulate matter and their removal efficiencies for BC should be relatively low.
- Closed crankcase emissions filtration device – A closed crankcase filtration device, by rerouting crankcase ventilation back to the engine, can be fitted to school buses and eliminate these emissions (Clean Air Task Force, 2005).
- Alternatives to diesel – It has been demonstrated that using biodiesel can reduce emissions of particulate matter (Clean Air Task Force, 2005; Lyons, 2003).
- Engine modifications – Particulates emissions can also be reduced through improvements to the basic engine such as turbo-charging, after-cooling, high-pressure fuel injection, retarding injection timing, and optimizing combustion chamber design (Lyons, 2003).
- Proper maintenance of diesel engines
- Reduce idling of diesel engines
- Replace gas lawn mowers with electrical mowers
- Reduce fuel consumption
- Reduce vehicle use

Effectiveness: Varies

Implementability: Varies

Reliability: Varies

Maturity: Varies

Environmental Benefits: Black carbon emission reduction

Cost Effectiveness: Varies

Industry Acceptance Level: Varies

Limitations: Varies

Sources of Information:

1. Bahner, M.A.; Weitz, K.A.; Zapata, A.; DeAngelo, B. (2007) "Use of Black Carbon and Organic Carbon Inventories for Projection and Mitigation Analysis", *Proc. 16th Annual International Emission Inventory Conf.*, Emission Inventories: Integration, Analysis, and Communications, Raleigh, May 14-17.
2. Battye, W.; Boyle, K.; Pace, T.G. (2002) "Methods for Improving Global Inventories of Black Carbon and Organic Carbon Particulates", Report No. 68-D-98-046 prepared for U.S. Environmental Protection Agency.
3. Clean Air Task Force (2005) "Diesel Engines: Emissions Controls and Retrofits", www.catf.us, v.3, revised 4-2005.
4. Cradle, S.H. (2004) "On-road Mobile Source PM and Black Carbon Emission Rates", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
5. DeAngelo, B.J. (2006) "Update of the EMF-22 Black Carbon", *Proc. EMF 22 Climate Policy Scenarios for Stabilization and in Transition*, Tsukuba, Japan, December 12-14.
6. Jacobson, M.Z. (2004) "Global Warming Impact of Black Carbon", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
7. Kleeman, M.J. (2004) "Emissions of Black Carbon in California", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
8. Lyons, K. (2003) "Assessment of Potential Strategies to Reduce Emissions from Diesel Engines in Washington State", a report prepared for Department of Ecology, State of Washington, Publication number 05-02-005.
9. Miller, C.A. (2004) "Carbon Emissions from Stationary Sources", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
10. Somers, J. (2004) "Mobile Source Black Carbon Emissions", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
11. Streets, D.G.; Bond, T.C.; Lee, T.; Jang, C. (2004) "On the Future of Carbonaceous Aerosol Emissions", *J. Geophys. Res.* Vol. 109, D24212.
12. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2006) "Regulatory Impact Analyses - 2006 National Ambient Air Quality Standards for Particle Pollution", United States Environmental Protection Agency, October 6, 2006.

Non-CO_2 Greenhouse Gases: Black Carbon

Source/Sectors: Stationary Sources

Technology: Options to reduce black carbon emission from stationary sources (D.2)

Description of the Technology:
Biomass burning accounts for approximately 25% of BC emissions in the United States. Biomass burning is a difficult source to control; however, from a global warming mitigation perspective, it may be less important because OC is more dominant in terms of emissions and negative forcing (DeAngelo, 2006). Most PM emission control measures on utility and non-electric generating utilities (non-EGU) point sources are add-on technologies. These technologies include fabric filters (bag houses), electric static precipitators (ESPs), and wet scrubbers (USEPA, 2006). Specific technological options to reduce BC emissions from stationary sources include the following:

- Mitigation measures for diesels – If diesel engines are used in the stationary sources, then the measures discussed in Section 5.1 may be applicable. For example, applying diesel particulate filters to diesel-fueled compression-ignition engines can achieve up to 90% reduction in fine particulate matter (USEPA, 2006). Other measures such as engine modification, alternative fuels, reducing idle time, and proper maintenance should also reduce BC emissions.
- PM control measures for area sources – Specific controls exist for stationary area sources, including catalytic oxidizers on conveyorized char-broilers at restaurants that can reduce PM emissions by 80% (USEPA, 2006). Another example is to replace older woodstoves with those in compliance with the New Source Performance Standard (NSPS) for residential wood combustion (USEPA, 2006).
- Apply the end-of pipe control on utility and non-energy generating utilities (non-EGU) point sources – Use ESPs, bag houses, or wet scrubbers for particulate removal. Upgrade the existing systems to better remove finer particles may be needed: one example is to add more collector plates in an ESP system to increase its removal efficiency (USEPA, 2006).
- Alternatives to open biomass burning – Available options to reduce open biomass burning include changing the frequency and conditions of prescribed burning and reducing open waste burning (US Climate Change, 2005).

Effectiveness: Varies

Implementability: Varies

Reliability: Varies

Maturity: Varies

Environmental Benefits: Black carbon emission reduction

Cost Effectiveness: Varies

Industry Acceptance Level: Varies

Limitations: Varies

Sources of Information:

1. Bahner, M.A.; Weitz, K.A.; Zapata, A.; DeAngelo, B. (2007) "Use of Black Carbon and Organic Carbon Inventories for Projection and Mitigation Analysis", *Proc. 16th Annual International Emission Inventory Conf.*, Emission Inventories: Integration, Analysis, and Communications, Raleigh, May 14-17.
2. Battye, W.; Boyle, K.; Pace, T.G. (2002) "Methods for Improving Global Inventories of Black Carbon and Organic Carbon Particulates", Report No. 68-D-98-046 prepared for U.S. Environmental Protection Agency.
3. Clean Air Task Force (2005) "Diesel Engines: Emissions Controls and Retrofits", www.catf.us, v.3, revised 4-2005.
4. Cradle, S.H. (2004) "On-road Mobile Source PM and Black Carbon Emission Rates", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
5. DeAngelo, B.J. (2006) "Update of the EMF-22 Black Carbon", *Proc. EMF 22 Climate Policy Scenarios for Stabilization and in Transition*, Tsukuba, Japan, December 12-14.
6. Jacobson, M.Z. (2004) "Global Warming Impact of Black Carbon", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
7. Kleeman, M.J. (2004) "Emissions of Black Carbon in California", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
8. Lyons, K. (2003) "Assessment of Potential Strategies to Reduce Emissions from Diesel Engines in Washington State", a report prepared for Department of Ecology, State of Washington, Publication number 05-02-005.
9. Miller, C.A. (2004) "Carbon Emissions from Stationary Sources", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
10. Somers, J. (2004) "Mobile Source Black Carbon Emissions", *Proc. Black Carbon Emissions and Climate Change: A Technical Workshop*, U.S. Environmental Protection Agency, San Diego, October 13-15.
11. Streets, D.G.; Bond, T.C.; Lee, T.; Jang, C. (2004) "On the Future of Carbonaceous Aerosol Emissions", *J. Geophys. Res.* Vol. 109, D24212.
12. U.S. Climate Technology Program (2005) "Technology Options for the Near and Long Term", U.S. Department of Energy, http://www.climatetechnology.gov/index.htm, August 2005.
13. U.S. Environmental Protection Agency (2006) "Regulatory Impact Analyses - 2006 National Ambient Air Quality Standards for Particle Pollution", United States Environmental Protection Agency, October 6, 2006.